LIFECYCLE ENERGY AND AIR EMISSION
DIFFERENCES BETWEEN ELECTRIC AND
INTERNAL COMBUSTION VEHICLES

THESIS

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I would like to thank my wife and son for putting up with me as I worked through the demands of the AFIT program; we're off to Hawaii!

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Abstract

The U.S. Federal Government has encouraged shifting from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs) with three objectives, reducing foreign oil dependence, greenhouse gas emissions, and criteria pollutant emissions. This thesis uses Monte Carlo simulation to predict lifecycle emissions and energy consumption differences per kilometer driven from replacing ICEVs with three EV options: lead acid, nickel cadmium (Ni-Cd), and nickel metal hydride (NiMH). All three EV options reduce U.S. foreign oil dependence by shifting to domestic coal. The probabilities that lifecycle energy consumption per km driven improve are lead acid 76%, Ni-Cd 64%, and NiMH 90%. The probabilities that EV substitution reduce global warming gas emissions are lead acid 41%, Ni-Cd 34%, and NiMH 64%. All three EV options increase sulfur oxides emissions. The probably that EV substitution will decrease nitrogen oxides emissions are only 12-14%. The probability that EV substitution reduces particulate matter emissions is less than one percent. The probability that EV substitution reduces volatile organic carbon emissions is lead acid 66%, Ni-Cd 98%, and NiMH 100%. Probabilities indicate that EVs will reduce foreign oil dependence, volatile organic carbon and lead emissions. However the other air emissions will increase and greenhouse gas emissions remain relatively unchanged.

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I. Introduction

General Issue

Over 90 percent of vehicles in worldwide service today are propelled by fossil fuel burning internal combustion engines (MacLean and Lave, 1999:1). The exhaust emissions from these vehicles contribute to air pollution resulting in deleterious impacts to the environment and human health. In addition to the effects of vehicular exhaust emissions, the consumption of refined crude oil for vehicle propulsion raises issues of sustainability and security for the U.S. as crude oil imports currently account for a significant portion of total oil consumption. The U.S. Federal Government has on several occasions created legislation and issued Executive Orders (EO) with the stated purpose of addressing these issues.

Problem Statement

This thesis evaluates the differences in lifecycle emissions, material consumption, and energy usage of four vehicle propulsion alternatives using a probabilistic computer model. The goal is to determine which alternative most effectively addresses the three stated goals of recent automobile legislation. These three goals are (Clinton, 2000:1):

1. Reduction in carbon dioxide (CO_2) emissions
2. Reduction in criteria pollutant air emissions
3. Reduction in foreign oil energy dependence

The four vehicle propulsion alternatives considered in this research are the conventional internal combustion engine vehicle (ICEV) and three types of grid dependent electric vehicles (EVs); the lead-acid battery EV, nickel cadmium (Ni-Cd) EV, and nickel metal hydride (NiMH) EV. The focus of this research is on the differences in the life cycle resource consumption and emissions for each alternative.

Background

The first goal of recent automobile legislation, a reduction in the emission of the greenhouse gas CO_2, is an issue of global impact. The fact that worldwide concentrations of CO_2 have risen is not in dispute. Atmospheric CO_2 levels have increased from approximately 280 parts per million (ppm) during pre-industrial times to almost 360ppm today (Joos, 1996:2). Data from entrapped air bubbles in arctic ice cores supports the theory that the origin of this increase is anthropogenic as opposed to natural (Joos, 1996:3). The ICEV is a significant source of anthropogenic CO_2. In 1997 approximately 31 percent of U.S. man-made CO_2 emissions were from fossil fuel combustion (EPA, 2000).

The second goal, criteria pollutant emissions reduction, has a more regional impact. Criteria pollutants are significant human health hazards and are identified by Sec. 201 of the Clean Air Act (CAA), also called the "National Emission Standards Act," as ozone (O_3), non-methane hydrocarbon (NMHC) or volatile organic compounds (VOCs), nitrogen dioxide (NOx), carbon monoxide (CO), particulate matter less than 10 microns in diameter (PM_{10}), sulfur dioxide (SO_2), and lead (USC,

549-101, 1992). ICEVs are the single largest source of U.S. air pollution accounting for 26 percent of VOCs, 32 percent of NOx, and 62 percent of CO emissions (Goehring, 1996:2). VOCs emitted by ICEV operations form tropospheric O_3, which is a respiratory irritant that, when combined with the two other major automotive emissions of CO and NOx, and energized by sunlight, form smog in many urban areas. This is a severe health hazard for persons already suffering from respiratory ailments such as emphysema or asthma (Utell, 1994:159). ICEV emissions are blamed for \$20-\$50 billion in estimated annual U.S. health costs (MacLean and Lave, 1999:3).

The third purpose, foreign energy dependence reduction, is significant because a large part of the fuel used by ICEVs in the U.S. is imported from foreign sources. According to a July 1996 report by the U.S. Department of Energy:

> Petroleum used in transportation alone exceeds total domestic oil production by 2 million barrels per day. This gap is growing, and is projected to reach nearly 6 million barrels per day by the year 2010. (DOE, 1996)

The U.S. imported 46 percent of total petroleum usage in 1996 (MacKenzie, 1997). By encouraging alternatively fueled vehicle (AFV) technologies, U.S. dependence on foreign oil can be reduced making the U.S. economy less vulnerable to perturbations in the global oil market.

Legislation

Clean Air Act

The deleterious air quality impacts of the ICEV were first addressed with U.S. federal legislation in the 1960s. The Clean Air Act of 1963 (CAA), amended in 1970, 1977, and 1990, was the first major legislative attempt to reduce automotive emissions in the U.S. The CAA and its amendments sought to improve air quality by specifying programs to control and reduce emissions of air pollutants. Section 246 of the Clean Air Act Amendments (CAAA) of 1990 requires that Federal and State-owned fleets purchase AFVs based on the air emission attainment status of the area in which the fleet vehicles operate (USC, 549-101, 1990). Generally speaking, each new piece of legislation placed constraints on the automotive industry not easily achievable at the time. Air regulations were designed to pull technology by providing motivation to improve automotive emissions controls and fuel technology.

Energy Policy Act

In addition to the motivation of clean air, the Energy Policy Act of 1992 (EPACT) sought to improve national energy security with an integrated national energy policy. EPACT established national goals for energy efficiency and fossil fuel use reduction (Public Law No. 486). With more efficient energy use, in everything from lighting and electric motors to ICEV gas mileage, energy consumption and net petroleum imports can be reduced. Current automotive technology is only 20-25 percent efficient (MacLean and Lave, 1999:1). Of all the energy released by the

combustion of gasoline, only 20-25 percent goes to drive the automobile while the rest is consumed mostly by internal friction and released as waste heat. The lifecycle energy efficiency of the ICEV is further reduced when vehicle manufacturing and gasoline production are considered.

To achieve the government's objectives, EPACT set specific AFV goals requiring that owners of fleets with more than 20 centrally fueled light duty vehicles located in metropolitan areas, defined as cities with a 1980 population of 250,000 or more, purchase AFVs. EPACT requirements in percent of new vehicles purchased each year that must be alternative fuel vehicles are shown in Table 1 (Honolulu Clean Cities Fact Sheet).

Model Year	Federal Gov't	State Gov't	Municipal Gov't & Private Fleets	Fuel Provider
1997	25%	10%		50%
1998	33%	15%		70%
1999	50%	25%		90%
2000	75%	50%		90%
2001	75%	75%		90%
2002	75%	75%	20%	90%
2003	75%	75%	40%	90%
2004	75%	75%	60%	90%
2005	75%	75%	70%	90%
2006	75%	75%	70%	90%

Table 1. Percent Vehicle Purchase Requirements of The Energy Policy Act of 1992.

EO 12844

To further encourage the development of AFV technology, on 21 April 1993 the Clinton administration issued EO 12844, "Federal Use of Alternative Fueled Vehicles" (Clinton, 1993). EO 12844 tasked federal government agencies to adopt

aggressive plans to exceed by 50 percent the AFV purchase requirements established by EPACT. The administration stated that by adopting aggressive purchasing of federal fleet AFV acquisitions there would be a reduction in the cost of AFVs resulting in a long-term movement toward increasing their availability as standard manufacturers' models (Clinton, 1993).

EO13031

EO 13031, "Federal Alternative Fueled Vehicle Leadership," superseded EO 12844 on 13 December 1996 (Clinton, 1998). The primary change from EO 12844 was that EO13031 gave double credit for the use of "zero emissions vehicles" (ZEVs) so that one ZEV was worth two AFVs. The term ZEV, generally referring to EVs, has received criticism, as these vehicles are not truly "zero emission "but" emission transference vehicles. While it is true that the EVs themselves emit no air pollution, the power plant that produced the electricity did. The EV transfers the emission burden from the automobile's tailpipe to the smokestack of the power plant producing the electricity. Ideally, by combining the emissions of many mobile sources into a single point source, regulation of emissions will be made easier because there are fewer sources to control and the sources are stationary. U.S. power plants are generally located outside metropolitan airsheds so, while air emissions still occur, air quality may be improved within the metropolitan areas. EVs also further national energy security objectives because the vast majority of U.S. power plants generally use domestic sources such as coal, uranium, and natural gas (Wang, 1992:351). By

shifting the primary source of energy from foreign oil to domestic resources, national energy security is improved.

The Department of Defense (DoD) was unable to achieve the AFV goals set by EO 13031. In Fiscal Year (FY) 1998, DoD reported to Congress that only 24.7 percent of new vehicle acquisitions in urban areas with populations exceeding 250,000 were AFVs (Oliver, 1998:2). The requirement for FY98 set by EPACT was 33 percent, which was increased to 50 percent by EO 13031. DoD anticipated an increase in the new vehicle acquisition rate to 49.5 percent in FY99, which is again short of the goal of 75 percent set by EO 13031 for FY99 (Oliver, 1998:2).

Oliver states that DoD consistently failed to attain the AFV fleet procurement goals as defined by EPACT and EO 13031 for three main reasons. First, the number of vehicles available for purchase was limited. Second, the available vehicles were prohibitively expensive. Third, the available vehicles were unable to fulfill the mission requirements.

Despite governmental attempts to enhance the AFV industry, the number of AFVs on the market remains limited. In FY97, DoD stated that only 11 suitable AFVs were available from major automotive manufacturers. However, four of these were either two-seat sports cars (EV-1) or full size sedans (Crown Victoria). Government class limitations precluded the purchase of very big or very small cars leaving only seven viable alternatives (Oliver, 1998:2).

In 1997, the DoD stated that AFV costs ranged from 44.7 percent to 54 percent more than conventional vehicles (Oliver, 1998:2). Worldwide only 10 percent of vehicles are powered by something other than internal combustion engines (MacLean and Lave, 1999:2). Additionally, DoD points out that the congressional funding support promised by EO 12844 for AFV procurement was never appropriated (Oliver, 1998:2).

Supply and cost not withstanding, many civilian and military fleet managers remained unwilling to purchase vehicles because they simply could not fulfill their mission requirements. Limited vehicle range and inadequate refueling infrastructure meant that AFVs could not travel far from their home fuel source. Fleet managers were unwilling to forgo the purchase of effective conventional vehicles to buy less effective AFVs at higher prices. One of the most popular AFV alternatives, compressed natural gas (CNG), met with resistance as the cost of a CNG vehicle averaged $4,500 higher than its conventional counterpart. DoD fleet managers resisted spending this additional amount for a bi-fuel CNG vehicle (runs on either CNG or conventional gasoline) when the vehicle would predominately operate on gasoline because of the lack of adequate CNG refueling infrastructure (Oliver, 1998:5).

<u>EO 13149</u>

The consistent failure of Federal Agencies to comply with EO 13031, in part, lead to its revocation by EO 13149, "Greening the Government Through Federal

Fleet and Transportation Efficiency" in April of 2000 (Clinton, 2000). EO 13149 is a new approach and changes tactics from simply mandating AFV purchasing requirements to combining those requirements with petroleum fuel consumption reduction goals for government agencies. EO 13149 still requires each agency to fulfill the acquisition requirements for AFVs established by EPACT for fleets in non-attainment areas. However, EO 13149 section 401 broadens the required purchase of AFVs to all geographic areas, not just non-attainment areas.

In addition, EO 13149 mandates a 20 percent reduction in petroleum consumption by the end of FY05 from a FY99 baseline. Section 202 of EO 13149 outlines several strategies for agencies to follow:

> "...the use of alternative fuels in light, medium, and heavy-duty vehicles; the acquisition of vehicles with higher fuel economy, including hybrid vehicles; the substitution of cars for light trucks; an increase in vehicle load factors; a decrease in vehicle miles traveled; and a decrease in fleet size...procurement of innovative vehicles, such as hybrid electric vehicles, capable of large improvements in fuel economy..."

Also included is a requirement to actually use alternative fuels in those vehicles capable of using them. Formally, an agency could purchase a dual-fueled vehicle to satisfy the EPACT requirement, then run the vehicle exclusively on gasoline and still receive AFV credit. This complied with the letter of the law as defined by EPACT, but gave no benefit to the environment. EO 13149 closes this loophole by requiring the "majority of the fuel requirements of those motor vehicles" capable of operating with alternative fuels be met with alternative fuels by the end of

FY05 (Clinton, 2000). In short, the Executive Branch was trying to encourage a market for the development of new AFV technologies (Clinton, 2000).

A new aspect of this EO is the improvement in the efficiency of the conventional component of the vehicle fleet. From EO 13149:

> "Agencies shall increase the average EPA fuel economy rating of passenger cars and light trucks acquired by at least 1 mile per gallon (mpg) by the end of FY 2002 and at least 3 mpg by the end of FY 2005 compared to FY 1999 acquisitions."

The AFV field is growing in response to both governmental and private sector interest. The number of AFVs manufactured by automotive companies is on the rise. In FY97, DoD stated that only 11 suitable AFV models were available. That number has jumped to 30 for model year 2000 (National Alternative Fuels Hotline, 2000).

In Honolulu, the Hawaiian Electric Company plans to install a network of up to 20 electric Rapid-Charger stations that will allow electric vehicles to recharge in less than 9 minutes. Hawaii offers an ideal place for electric vehicle use as the climate reduces battery thermal management problems and the geographic limits of islands guarantee that no driver could ever stray beyond a network of charging stations. Also, most trips are within the range offered by current battery technology. Hawaiian motorists do not need a vehicle capable of long-range interstate travel so EVs may serve as their primary vehicles (State of Hawaii, 2000).

Research Objective

It is clear that the AFV and alternative fuel industries are being stimulated by national interest, but the question remains, what technology or combination of technologies best fulfills the government's stated goals of reducing CO_2 emissions, criteria pollutant emissions, and foreign energy dependence? The goal of this research is to determine which, if any, of the emerging EV technologies should be encouraged to most effectively achieve the stated goals. Past automotive academic research has focused primarily in the areas of fuel consumption and emissions for ICEVs and EVs. Past research tends to be narrowly focused on the production, use, or disposal phase of the product's lifecycle and the raw material acquisition and processing phases have typically not been included. This thesis will compare EV and ICEV total life cycle emissions to include raw material acquisition.

The reason for focusing on the grid dependent EV and the ICEV is that these two platforms represent the extremes for possible future transportation paradigms. Any grid dependent EV will require some form of energy storage and will rely on the national power grid for energy. Any vehicle using alternative fuels such as bio-diesel or methanol will be an internal combustion platform and share consumptions and emissions with today's ICEV. A hybrid vehicle propulsion system will be composed of some blend of the ICEV prime mover and the EV energy storage systems.

II. Literature Review

Transportation Paradigm Shift

Health authorities saw the ICEV as an end of manure heaps, disease-carrying flies, and assorted other animal pollution resulting from the use of draft animals such as horses and mules. Until the advent of the ICEV, the horse had been the primary means of personal transport. It is estimated that 24,000,000 horses were in use in the U.S. in 1910 (Deuel, 2000). Supporters of the automobile pointed out that in addition to horse pollution, horses were a great burden on the economy, as each horse in the U.S. required the production of five acres of land and twenty man-days of work per year. Ransom E. Olds advertised a new steam carriage: "It never kicks or bites, never tires on long runs, and never sweats in hot weather. It does not require care in the stable and eats only while on the road" (Scientific American, 1892).

The horse had some support however. Horses were an important part of the economy with livery and veterinary bills amounted to millions of dollars each year. The technological development of the automobile rendered entire industries obsolete. Harness makers, buggy-whip companies, carriage builders, livery stable operators, blacksmiths, street cleaners, wheelwrights and even hitching-post manufacturers all had to re-tool or face unemployment as a result of the horse's declining popularity. These people resisted the automobile as an end of their livelihood (ICP: 1999).

The modern ICEV is the result of years of research and evolution. The alternatives to ICEV currently under exploration by the automobile industry, such as

EVs, seem new and innovative but most have been known for many years. One of the first serious propulsion methods employed were steam-powered, external combustion engines. The use of steam power for vehicle propulsion was an outgrowth of the industrial steam engines designed by James Watt. However, these machines proved so noisy, and unpopular, that in 1865 the British Parliament adopted the "Red Flag Act," which limited steamers to a speed of four miles an hour on the open road and to two miles an hour in the city. The operation of a steamer required a crew of three men: one walking sixty yards ahead, with a red flag by day and a lantern at night, to warn of the vehicle's approach (ICP: 1999).

Because of these restrictions, inventors looked for a quieter means of locomotion and turned to electric power for their vehicles. The first EV is believed to have been built in Scotland about 1839 by Robert Anderson (ICP: 1999). It was quiet and could start immediately, whereas the steam vehicle had to wait for a boiler to build up pressure before moving. But there were disadvantages; electric batteries were heavy, bulky, and needed recharging after traveling a short distance. Despite its drawbacks, this propulsion method enjoyed moderate success. Electric cabs appeared on the streets of London in the late 1800s. In France, Camille Jenatzy, driving a Jeantaud EV, attained the record speed of sixty miles per hour on April 29, 1899 (ICP: 1999). At the peak of the EV's success in America, 20 different car companies were producing them and in 1900 electric vehicles had 38 percent of the automobile market (Horseless Age, 2000).

However, range limitations between recharging eventually lead to a decline in the popularity of the EV. The 1897 Riker Victoria EV had a range of approximately 20 miles per charge. The vehicle manufacturer held the batteries responsible for the range limitation claiming that they had "...yet to learn of a battery of high-efficiency and low-depreciation, which was the type required..." for electric vehicles (The Horseless Age, September 1897:8). The turn of the century saw a new dominant technology emerge that overwhelmed all other forms of automotive propulsion, the gasoline-fueled ICEV.

Like most technologies, the ICEV matured gradually. Internal-combustion engines had been in development since 1860. Etienne Lenoir applied to the authorities in Paris for a patent on his engine powered by coal gas. In Germany, Carl Freidrich Benz obtained a patent on his one cylinder, 0.9 horsepower motorcar in 1886 (Mercedes-Benz, 2000).

The first popular U.S. ICEV was a two-passenger roadster, the "Oldsmobile," designed as an economy car by Ransom E. Olds. This car had two seats and a one-cylinder, three-horsepower engine. In 1914, Henry Ford opened the world's ICEV assembly line producing 472,000 cars a year, one every 93 minutes. In 1924, half of the cars in the world were Fords. By 1927, Ford Motor Company had manufactured 15,007,003 Model Ts.

Automotive Emissions

While the ICEV did relieve cities of animal pollution, it has been recognized as a major source of air pollution since the 1940s (Utell, 1994:157). Motor vehicles are the primary source of urban CO and are a major source of VOCs and NOx emissions responsible for the formation of photochemical smog and ground level ozone (Beaton, 1995:1). To mitigate ICEV health effects, the U.S. Government regulates automobile emissions at an estimated annual cost to the automotive industry of up to $12 billion annually (Utell, 1994:157). Automobile emissions and their atmospheric derivatives are typically characterized in one of three ways (Utell, 1994:1, MacLean and Lave, 1999:1):

1. Regulated or criteria pollutants
2. Unregulated pollutants
3. Greenhouse gasses

The regulation of automobile emissions has come about primarily due to significant human health effects (Utell, 1994:175). As listed in Chapter 1, the regulated pollutants are: O_3, VOCs, NOx, CO, PM_{10}, SO_2, and lead (USC, 549-101, 1992). Unregulated pollutants include any compound emitted that may cause harm to humans and for which no specific standard exists. Greenhouse gasses are those gasses believed to have global warming potential. These emissions primarily include CO_2, methane, and nitrous oxide; however, only CO_2 is directly emitted by ICEV operations in any significant quantity with respect to global warming potential (MacLean and Lave, 1999:227).

Each ICEV emission has unique impacts. To understand the impacts of automobile emissions, a brief summary of the emissions modeled in this research is as follows.

Ozone, NOx and VOCs

This research models VOC and NOx emissions that are indirectly responsible for ground-level ozone formation. Automobiles do not directly emit ozone. Ozone naturally occurs in low concentrations but when VOCs chemically react with NOx in the presence of sunlight; ozone concentrations can reach dangerously high levels. The health effects of ozone are most directly felt among susceptible sub-populations, such as asthmatics. Health effects include breathing problems, reduced lung function, stuffy nose, and may have chronic effects such as bronchiolitis (Utell, 1994:175).

Automobiles directly emit VOCs through fugitive evaporative emissions and incomplete combustion. Calvert *et al.* characterize the automobile's evaporative VOC emissions in four ways: diurnal releases, hot soak, running losses, and refueling evaporation. Diurnal release occurs as gasoline evaporates and the fuel tank "breaths" emitting as much as 50g of VOCs on a hot day. Hot soak emissions occur just after the engine is shut down and heat from the engine evaporates fuel in the automobile's fuel system causing it to vaporize and escape through the system vent. Running losses occur in a similar manner as hot soak emissions but while the vehicle is in motion. Refueling emissions occur when the fuel cap is removed to fill the vehicle's tank. In addition to evaporative losses, VOC emissions occur as a result of

the combustion process. Incomplete combustion of petroleum hydrocarbons when the vehicle is using a rich fuel mixture allows VOCs to escape through the vehicle's exhaust system with combustion waste gasses (Calvert *et al.*, 1993:38). VOC emissions modeled in this research account for VOC emissions from all these sources.

Automobiles directly emit NOx as the combustion process uses ambient air, which contains 78 percent nitrogen. Atmospheric nitrogen is normally inert; however, when combined with oxygen at high temperatures, such as an automotive combustion chamber at 2,500° F, NOx forms (ICP: 1999). The direct health effects of NOx are similar to ozone and generally affect the respiratory system (Utell, 1994:175). Direct environmental effects of NOx emissions include its transformation into nitric acid, a component of acid precipitation and a source of increased visibility impairment. The U.S. Environmental Protection Agency (EPA) estimates that up to 40 percent of the nitrogen "loading" in the Chesapeake Bay is the result of rainout of air-borne nitrogen oxides (Parker and Blodgett, 1999).

Carbon Monoxide (CO)

CO is directly emitted as a combustion byproduct. When inhaled, CO reduces the ability of blood to transport oxygen to tissues. CO may be particularly hazardous to people who have heart or circulatory problems. Smokers, who already have a relatively high blood CO concentration, are particularly susceptible to the health effects of added CO exposure (Utell, 1994:175).

Particulate Matter Less Than 10 Microns in Diameter (PM_{10})

PM_{10} is specifically identified because these particles can penetrate deeply into lung passages, whereas larger particles tend to be harmlessly filtered out by the upper respiratory system. PM_{10} is directly emitted by automobile combustion exhaust as well as through break pad and tire deterioration. PM_{10} emissions are larger for engines using diesel fuel because of diesel fuel's high molecular weight relative to gasoline (Wang et al., 1997:3135). Exhaust PM_{10} from ICEVs is composed of carbon particles that are themselves not of great concern. The detrimental effects of PM_{10} come as a result of chemicals such as benzene, a known human carcinogen, sorbed in the carbon particle interacting with human tissue (Utell, 1994:162).

Oxides of Sulfur

SOx is emitted from ICEV operation because of sulfur impurities present in fossil fuels. SOx released primarily by fossil fuel combustion reacts with water to form acid rain, which acidifies soils, particularly forest soils with low buffering capacities and can damage both aquatic and terrestrial ecosystems and stone structures such as monuments. This acidification causes normally fixed metals in soils, such as aluminum, to mobilize in concentrations that are toxic to some plants and fish.

Lead

Lead was formerly emitted directly by automobiles when tetra alkyl lead was added to leaded gasoline as a knock inhibitor. Lead was completely phased out in the

U.S. in 1993 (Utell, 1994:162). Lead is persistent in the environment and air emissions tend to mobilize in water eventually exposing humans, for this reason all lead emissions are of concern (Lave *et al.*, 1995:995).

Life Cycle Assessment

When ICEVs were introduced, the air pollution that would result was not well understood at the time. As discussed in the introduction, the U.S. Government has sought to limit criteria pollutant emissions and reduce foreign energy dependence through, among other things, legislation encouraging changes in the makeup of the automobile fleet (Clinton, 2000:1). The problems these goals address are complex and an improvement in one area could easily cause deterioration in another. All aspects of the manufacture, use, and disposal of a product should therefore be considered thoroughly to understand all impacts when a product shift is implemented. Life Cycle Assessment (LCA) is particularly well suited to address this type of complex problem.

LCA can reveal problems not immediately apparent. For example, replacing steel automobile components with lighter aluminum seems like a good idea since lower vehicle weight will improve gas mileage, thus saving energy. However, primary aluminum production is energy intensive and the additional energy expenditure in the manufacturing phase could actually offset any benefit realized in the operation phase of the product's lifecycle (Stodlsky, 1995:7). When the entire lifecycle perspective is applied, this action could actually cause the total vehicle

lifecycle energy requirement to increase. This is just one example of a situation where an improvement in one area of a product's lifecycle could worsen its overall environmental impact.

LCA is an environmental management process that quantifies the energy and materials used and wastes released to the environment during all phases of the life of a product. Product life cycle is divided into resource extraction, material preparation, manufacture, use, and final disposal (Gloria *et al.*, 1995: 33). LCA is not designed to provide product economic life cycle cost but instead focuses on its environmental performance (Sullivan and Young, 1995:38). LCA is a four-step process: goal definition, life cycle inventory (LCI), impact assessment, and improvement analysis (Sullivan and Young, 1995:38-40).

Goal definition helps to focus the considerable effort required in conducting an effective LCA. Defining the goal guides the development of the system boundaries, assumptions, and data requirements. The LCA process recognizes that adjustment of the goals may be required as the LCI progresses through the other steps (Sullivan and Young, 1995:38).

LCI is the process of identifying a product's various inputs and outputs in energy, wastes, and resources for each phase of its lifecycle. The output of the LCI is typically presented in an inventory table detailing inputs, outputs, environmental emissions, and any other impacts from the product's lifecycle (Gloria *et al.*, 1995: 34).

Impact assessment is the stage of LCA wherein the environmental burdens identified by the LCI are quantitatively or qualitatively characterized. In the impact assessment stage of LCA, some statement about the scope of the impact, local or global, is appropriate. The LCA process is appropriate for strategic decision-making as it considers the broad impacts of change that may reveal instances when local optimization shifts environmental burdens such as emissions to other stages of the life cycle. Potential improvements in a product's environmental burden should be considered along with other environmental impacts to develop an appropriate decision framework. (Gloria *et al.*, 1995:34).

Techniques used to evaluate environmental impacts are poorly developed at this time. In general, a "less is better" approach is typically adopted. However, this approach falls short in situations where a change reduces one burden while increasing another because there is no generally accepted method that allows dissimilar effects to be easily compared (Sullivan and Young, 1995:38-39). LCA is appropriate for complex problems because a change made in one facet of a process or a product may have hidden consequences. An examination of some of the terminology in recent legislation indicates that the life cycle approach has not been fully embraced. For example, EO 13031 refers to EVs as "zero emission vehicles" (ZEVs). But in the life cycle perspective, EVs do have emissions as a consequence of their operation (Clinton: 1996). The electricity for EV locomotion comes from the national power grid, primarily from the burning of coal, which still produced emissions, though the

type and location of the emissions may change with a shift in the vehicle fleet makeup. Also, several studies show that with conventional lead-acid, batteries these vehicles could, in some aspects, have a greater detrimental effect on the environment than conventional ICEVs. Lave cites increased lead emissions resulting from lead smelting for battery manufacture (Lave, 1996:406). Finally, vehicle disposal will generate solid waste, some potentially hazardous, as no vehicle is 100 percent recyclable (Tansel, 1997:2).

The Electric Vehicle

To understand the environmental impacts of a shift from the ICEV to the EV, it is worthwhile to examine the major factors impacting EV performance. Because the EV relies solely on batteries for its energy storage, the limiting parameters for EV performance are range, acceleration, average velocity, and discharge rate (Lave *et al.*, 1995: 994).

Range is determined by energy storage capacity. Energy storage capacity is achieved either by equipping the EV with more batteries or by increasing the energy density of the batteries. Energy density is measured in watt-hours per kilogram (Wh/kg). As the units suggest, this is a measure of how much energy is stored on a full charge for every kg of battery mass. Lead acid batteries, commonly used for starting ICEVs, typically have an energy density of 38 Wh/kg (Lave *et al.*, 1995: 994). For comparison, gasoline has an energy density of approximately 13,000 Wh/kg (Lave *et al.*, 1995: 994). The U.S. Advanced Battery Consortium (USBAC), a

group of private companies brought together by the Department of Energy (DOE) in the interests of advancing battery technology, has set a goal of 100 Wh/kg for the advanced nickel metal hydride battery (NiMH) and reports a value of 80 Wh/kg (Ovshinsky, 1993:177). Increasing the total battery mass on the vehicle increases the range, but the increased mass decreases other performance factors like acceleration.

Vehicle acceleration is limited by the vehicle power-to-weight ratio. Acceleration can be improved by decreasing vehicle weight or increasing vehicle power. For an EV, power is determined by the battery specific power measured in watts per kilogram (W/kg). This is determined by chemical reactions within the battery and is reported at a current value of 150 W/kg with a future goal value of over 200W/kg (Ovshinsky, 1993: 177). For the ICEV, power is determined by how quickly fuel is combusted and can be increased by either increasing the combustion chamber volume or increasing the amount of air/fuel mixture in the chamber by forced induction.

Discharge rate and average velocity are inversely related. The vehicle energy requirement, or discharge rate, measured in Wh/km, determines how quickly the batteries are drained. Analogous to the ICEV efficiency rating in miles per gallon (mpg), vehicle energy requirement is determined by the vehicle-operating scenario. The EV must rely on batteries for parasitic loads such as the air-conditioner, radio, lights, and any other electrical device. These parasitic loads detract from the maximum range and velocity. One reported value of EV total energy requirement is

310 Wh/km, which is the sum of parasitic loads and vehicle propulsion loads (Lave *et al.*, 1995: 994). For comparison, a gasoline ICEV rating of 30 mpg equates to an energy requirement of 755 Wh/km so the EV cited by Lave is much more thrifty than most ICEVs.

Another aspect of the EV is the battery life, which is characterized by the total distance a set of batteries will take the vehicle before their performance deteriorates, battery life-cycle distance measured in kilometers. Typical values for current technology are reported as 36,000 km, while the USBAC goal is 80,000 km (Lave *et al.*, 1995: 994). Another way to rate battery life, independent of vehicle distance, is cycle-life measured in cycles for a given depth of discharge (DOD). A cycle is the complete process of discharging the battery through use then recharging it from the power grid. DOD measures the amount of battery charge used in the cycle. For example, a battery that has used half of its stored energy has a DOD of 50 percent. Fully discharging batteries in operation shortens their life so manufacturers commonly recommend a DOD of 80 percent. With an 80 percent DOD, NiMH batteries are reported to last 600 cycles with a goal of 1000 (Ovshinsky, 1993:177). However, in operation users will recharge at less than optimal intervals and therefore shorten power pack life. The reason battery life is important is that significant emissions are generated by the manufacture of power packs. When power packs must be replaced often, an increase in lifecycle emissions and resource consumption will occur.

A water analogy may be helpful to clarify these EV parameters. Imagine a water tower with a pipe attached to a turbine driving some load. In this analogy, there are two ways to increase the stored energy: increase the height of the tower, thus provide more energy for a constant mass, or add more water. The stored energy in an EV power pack is also composed of two parts; the amount of water in the tank is the power pack mass and the height of the tank is the energy density. The height of the imaginary tank is increased through battery technology, by improving the energy density, and is relatively fixed for a given battery type. Adding more batteries increases the amount of water in the tank, but this increases vehicle weight. Battery specific power is analogous to the size of the pipe leading from the water tower to the turbine. A bigger pipe means more flow, more water per unit time. However, a high flow rate quickly empties the tank and depletes the energy stores. The load on the water turbine is analogous to the vehicle energy demand. A high load means lots of water is necessary to turn the wheel so a given amount of stored energy does not last long. The challenge for EV designers is to balance the range of the vehicle and the weight of the batteries to provide a useful range and acceptable acceleration performance.

Monte Carlo Simulation

The U.S. Government is encouraging the replacement of the ICEV by the EV with the hope that pollution and foreign energy consumption will be reduced. As with the shift from the horse to the ICEV for personal transportation, the move form

the ICEV to the EV may result in unforeseen consequences. Vehicle emission research tends to be narrowly focused on a single lifecycle phase (usually the use phase) and neglects to consider a range of possible emission factors from other phases. In addition, emissions models in widespread use assign a single deterministic value to each input variable and arrive at a single deterministic solution (U.S. DOT, 1994). This method yields a value for the model output that does nothing to express the certainty of its estimate. These deterministic estimates fail to place point estimates in the context of the uncertainty in which they were developed (Finkel, 1994:381).

A better way to apply the LCA model to estimate emissions from the EV and the ICEV is to use Monte Carlo simulation. Monte Carlo simulation is a technique of simulating real world behavior with variable distributions instead of deterministic point values (Crystal Ball, 1996). This technique is widely used in the human health risk assessment community (Copeland *et al.*, 1994, 1399-1400).

Monte Carlo simulation is superior to traditional deterministic methods because it allows the modeler to account for the uncertainty in each of the input variables and predict the impact of that uncertainty on the model output. This technique provides the decision maker with the range of potential outcomes and the predicted relative chance of their occurrence (Finley and Paustenbach, 1993:55).

The simulation construction is a three-step process. First, input variables are identified and a distribution determined from real world or theoretical data is assigned

to each variable. The assigned distribution of each variable is intended capture the central tendency and variability of that input variable. The appropriate descriptors of the distribution, such as mean and variance, are determined and input to the Monte Carlo simulation. The second step is running a simulation through software designed to perform Monte Carlo simulation. The software used in this study is Crystal Ball from Decisioneering Inc. (Decisioneering, 1996). The model randomly selects values from each set of input variables and generates outcomes in a probability density curve. Typically, a minimum of 5,000 iterations is needed to ensure a point of convergence is reached (Copeland *et al.*, 1993:277). In this study, 10,000 iterations were conducted. The third step is generating the model output. The output variable results from each iteration are combined to construct a relative frequency histogram that becomes the probability distribution function (PDF) for the output of interest, called the forecast variable. This PDF expresses both the predicted central tendency and the variability in the forecast variable arising from the variation in the input variables.

Figure 1 illustrates the difference between Monte Carlo simulation and a deterministic model. Models in widespread use, such as EPA's mobile source emissions model MOBILE, use a single factor to characterize the emissions for a class of ICEVs (U.S. DoT, 1994). As a vehicle ages, its emission control systems, primarily the catalytic converter, become less effective and cause emissions to increase.

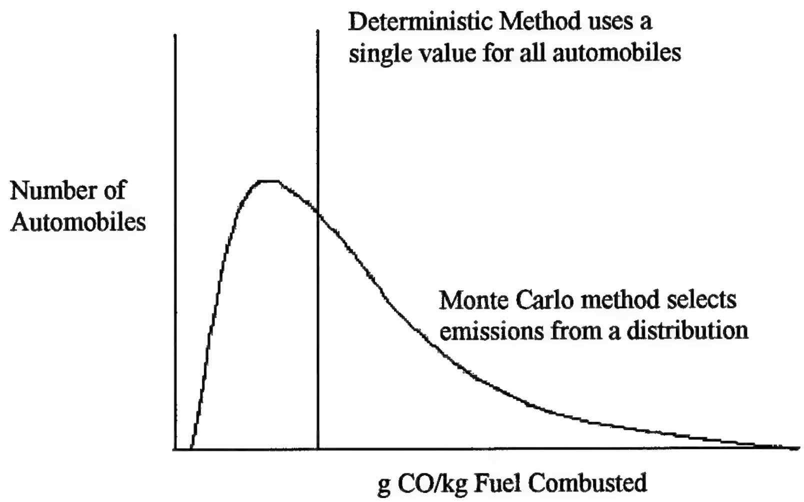

Figure 1. Example of Deterministic and Stochastic Modeling.
Automobile emissions are known to be gamma distributed but most models restrict them to average values ignoring outliers, and as a result, underestimate emissions.

This phenomenon is called emissions deterioration (Winebrake and Deaton, 1997: 1291-1292). The MOBILE model characterizes the emissions deterioration of a vehicle by specifying a slope and intercept. The intercept value is the emissions value when the vehicle is new and the slope is the rate at which the emissions increase over the lifetime of the vehicle in years or miles (U.S. DOT, 1994: 28-30). So when estimating emissions, MOBILE assigns the same factor to every ICEV in a particular year group.

A major drawback of this technique is that it assigns a single value to each vehicle of a given make and year and does not allow for the possibility that a vehicle will become a gross polluter through emission system failure caused by converter

poisoning or removal through criminal tampering. By ignoring the possibility that some ICEVs can exhibit very high emissions because of pollution control device failure, the models underestimate some emissions (Pierson *et al.*, 1995:2234). By specifying a distribution instead of a point value, a better approximation can be developed, as the so-called outliers are included in the model.

Another area where Monte Carlo methods are useful is emission factor development. The emission factor expresses how much pollutant emission, material input, and energy input are required to produce one unit of the material specified. For example if the energy input factor for aluminum is 86 MJ/kg, then 86 MJ of energy must be input into the system to manufacture 1 kg of aluminum. These factors are applied to calculate the manufacturing phase environmental burden of a material as:

$$\textit{Mass of Material (kg)} * \textit{Emission Factor (kg/kg Material)} = \textit{Pollutant (kg)} \qquad (1)$$

Developing an accurate factor is difficult. The literature has many contradictory factors, and references to "unpublished information" (Stodlsky 1995:13). For example, the EPA AP-42 database is the most widely used air emissions factor database available without substantial monetary expense (Overly 1999: 2-3). It is widely recognized however that some of these data are of "average" quality (Overly 1999: 2-3). Because deterministic models rely solely on a single number to estimate emissions and make no allowance for the uncertainty in that factor, the only way to

improve their resolution is to improve the accuracy of the assumed emissions factors. This is difficult however, as industries understandably desire confidentiality with respect to the pollution they emit (Maclean and Lave 1998:323). Gathering data to develop accurate emission factors is often expensive and time consuming, sometimes taking years to compile (Sullivan, 1998:1).

Because assumed emission factors have a significant influence on the result of a study, the emissions factors are often the cause of controversy. In his 1995 study "Environmental Implications of Electric Cars," Lave stated that a "1998 model electric car is estimated to release 60 times more lead ... relative to a comparable car burning leaded gasoline" (Lave, 1995:995). The response of the scientific community was "astonishing in terms of the level of attention, venom and desire to defend EVs" (Lave, 1995:744). This result was based on an emissions factor for lead emitted of 2 to 4 percent of lead production (Lave, 1995:994). Monte Carlo simulation is well suited to deal with the uncertainty inherent in emission factor estimation and can eliminate the "counterproductive and sometimes polarizing discussions that center around selecting the best point estimate" by specifying not a point estimate but a range incorporating more than one point of view (Finley and Paustenbach, 1994:56).

The selection of factors and other assumptions can change the results of a study. For example, assume a vehicle is redesigned to replace steel components with aluminum to improve use phase efficiency. Assume that aluminum manufacture is more energy intensive than steel manufacture and that as a result, manufacturing

energy input increases. If the vehicle has a long use phase, then the savings in the use phase offset the additional energy required for manufacture. However, if the use phase is short, then from a lifecycle perspective, energy consumption actually increases with the addition of aluminum components. Therefore, the use phase length assumption skews the result of a deterministic study. If research is conducted from a "pro-aluminum" perspective then a long use phase is assumed. Conversely, if research is "pro-steel" then a short use phase will be assumed.

III. Experimental Methods

Modeling Assumptions

The goal of the study was to evaluate the lifecycle differences in emissions and inputs between the ICEV and three types of EVs: the $EV_{lead\text{-}acid}$, EV_{NiMH}, and EV_{NiCD}. The Monte Carlo technique will be used to model the differences and demonstrate the use of Monte Carlo simulation in LCA. With the ICEV as the baseline, each EV alternative was compared to the ICEV as shown below:

$$ICEV_{emission\ or\ input} - EV_{(lead\text{-}acid,\ NiMH,\ Ni\text{-}Cd)\ emission\ or\ input} = Net\ Difference \qquad (2)$$

The results of this study are intended to provide the decision-maker responsible for choosing an EV option with environmental impact information, including energy use, and emission differences relative to the ICEV. Therefore, equation 2 indicates that if an emission or input is lower for the EV, then the net difference will be positive and if the EV emission or input is higher, then the net difference will be negative.

Any similarities between an EV platform and ICEV will not be evaluated in the scope of this research. Common inputs and emissions would cancel out and thus not be significant factors in deciding the best vehicle propulsion alternative. Examples include emissions and inputs from the manufacture and use of tires, glass, and paint common to both the ICEV and the three EV types. Focusing on the differences in the options allows several simplifying assumptions in the model as discussed in the lifecycle overview.

The vehicle modeled is a mid-size sedan as presented by Sullivan (Sullivan and Hu, 1995). This vehicle is selected because it is the most likely to be purchased by the DoD to satisfy fleet purchase requirements outlined previously. The infrastructure necessary to charge and service new EVs is assumed to be a small component of overall life cycle emissions and is not analyzed in this research.

The overall structure of the model is to first determine the lifecycle differences in the mass of each material consumed during manufacture and maintenance by each EV type relative to the ICEV. The total material mass consumed is a function of the manufacturer's design decisions regarding the materials to use in component construction and vehicle design range. The vehicle lifecycle length primarily determines the total mass of material consumed in vehicle maintenance. The emissions generated and inputs required to manufacture the materials used during construction and maintenance activities are then found by multiplying the mass by an emission or energy input factor. These factors were developed considering the amount of materials currently recycled and the emissions and energy savings realized. In addition to material consumption, the model evaluates the energy consumed by each vehicle during the use phase of its lifecycle. Energy consumption and emissions per km driven are determined by the energy input in material manufacturing, mass of material consumed, vehicle efficiency, total distance traveled during the lifecycle, and the efficiency and emissions of the process providing the energy, which are all model parameters discussed in detail in the

following sections. ICEV use phase combustion emissions are also estimated based on gamma distributions for pollutants that allow for an ICEV to become a high emitter. Because this is not a deterministic model, the final model outputs are not single numbers but a range of possible values for each parameter estimated. Each aspect of model formulation will now be discussed.

Lifecycle Overview

Figure 2 depicts a simplified view of the overall automobile lifecycle. A grayed-out box indicates an area that was ignored based on the assumption that each type of EV and the ICEV are equivalent with respect to environmental impacts. Some examples are marketing, shipping, and assembly. The assumption that assembly is equivalent is a potential weakness in the model as the EV is simpler and possibly easier to assemble thus requiring less assembly energy. In addition, the disposal phase of the lifecycle could exhibit major differences. For example, the inappropriate disposal of lead-acid battery packs would release substantial amounts of lead into the environment (Lave, 1995: 994).

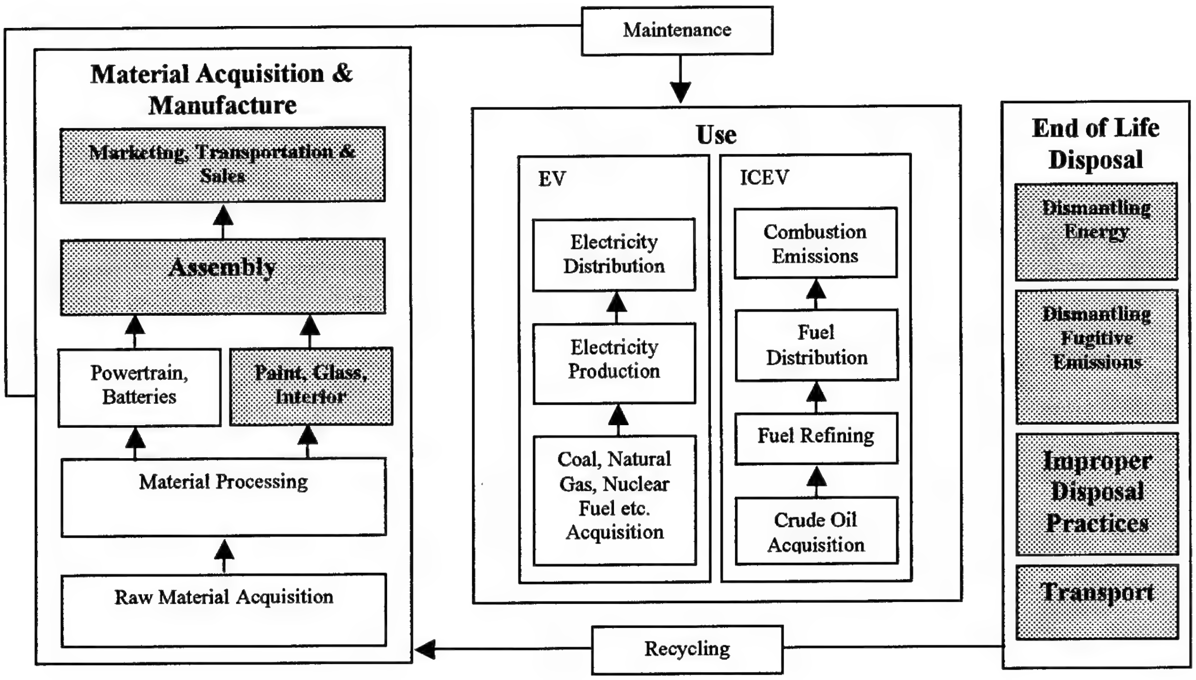

Figure 2. Simplified Automobile Lifecycle.
(Adapted from MacLean and Lave, 1998:323) A grayed-out box indicates that all automobile options are considered equivalent in that area.

Material Consumed Mass Assumptions

Determining the differences in vehicle material mass consumption was done by first identifying the areas of similarity. Table 2 lists a breakout of vehicle systems along with the assumed commonality between systems. Because this research is focused on the differences in the vehicle propulsion platforms, areas that are "fully common" were not evaluated in this study. For example, it was assumed that each vehicle would have the same amount of rubber in the tires and that rubber would be consumed at the same rate. Therefore, tire rubber consumption is ignored in this model. This is a potential weakness of the model because lead-acid EV would

probably use tires faster than the ICEV because the EVs tend to be heavier than the other platforms for an equivalent range. Also, different tire sizes and load ratings may be necessary to accommodate the additional weight of an EV. Another example of a fully common material between all vehicles is glass. It is assumed that each vehicle would have exactly the same amount of glass and use glass at the same rate throughout the vehicle lifecycle. Therefore, glass is not evaluated in this study.

The emissions and inputs associated with areas listed as "somewhat common" and "not common" in Table 2 were considered in this study. An example of a "somewhat common" component is the lead-acid starter battery in the ICEV, which is included in the power train. The starter battery and the lead-acid EV power pack are essentially composed of the same materials, except the lead acid EV power pack is much larger. The emissions and inputs for each were therefore evaluated based on an equivalent mass composition with the mass of each material scaled to the total mass of the battery.

Vehicle Group and Subgroup	Fully Common	Somewhat Common	Not Common
Body Group			
Body-in-white	X		
Paint and coatings	X		
Glass	X		
Interior body trim	X		
Exterior body trim	X		
Seats	X		
Instrument panel		X	
Restraint system	X		
Body electrical components	X		
Heating, ventilating, and air-conditioning (HVAC)		X	
Engine Group			
Base engine			X
Emissions control			X
Engine accessories			X
Engine electrical components			X
Cooling system			X
Transmission Group			
Transaxle			X
Clutch and actuator			X
Transmission controls			X
Chassis Group			
Frame	X		
Suspension	X		
Steering		X	
Brakes		X	
Exhaust system			X
Fuel storage			X
Final drive	X		
Wheels and tires	X		
Bumpers, fenders, and shields	X		
Chassis electrical components		X	
Accessories and tools	X		
Fluids		X	

Table 2. ICEV and EV Platforms Similarity Data.
(Cuenca *et al.*, 1999:10)

Once the systems to evaluate were identified, the materials involved in the construction of those systems were determined. Several factors influence manufacturers' material selection including material weight, cost, manufacturing techniques, and government requirements (Kandelaars and van Dam, 1998:235). The

materials used in vehicle component construction can have a significant effect on life cycle emissions and inputs. The extraction and processing of each material has unique environmental impacts. Material selections, such as an aluminum body instead of a steel body, may have a dramatic impact on the aggregate environmental burden (Kandelaars and van Dam, 1998:324).

For modeling purposes, the vehicle mass was divided into vehicle components and battery components. This was done because a great deal of uncertainty exists in the battery composition, while the body composition is well known. It is unlikely that further improvements will be made in body material composition as the EV and ICEV vehicles have already been thrifted to the maximum extent possible to improve efficiency (Sullivan and Hu, 1995:7). Battery composition, however, is determined by vehicle design considerations such as range. Also, battery composition is proprietary information and not readily available.

Table 3 shows the vehicle component mass assumed for each material listed. Petroleum based fluids such as automatic transmission fluid, bake and steering fluids, as well as motor oil, were assumed to have the same manufacturing emissions and inputs as gasoline due to a lack of emissions and input data. It is worthwhile to note that the EV is nearly maintenance free during the use phase while the ICEV requires a significant amount of maintenance materials. EV maintenance mass is expressed entirely in the replacement of the power packs.

EV power pack mass is dependent on vehicle performance assumptions, including range and battery energy density. The model determined the total battery-pack mass by first selecting within defined distributions a vehicle range, then a battery energy density. Once these factors were determined, the power pack mass required to achieve the selected range was computed in the model. The material composition of the power pack was then determined by breaking up the power pack into its component materials based on the percentage composition shown in Table 4. Replacement ICEV starter batteries were assumed to have the same composition as the lead-acid EV power pack.

	Primary Mass (kg)		ICEV Maintenance Mass (kg/100,000 km)
Material	**ICEV**	**EV**	
Iron & Steel	822	230	80.2
Copper	18	140	8.85
Aluminum & Magnesium	58	259	65.1
Plastic	127	376	57.8
ATF, Brake, Steering Fluids	4	18	8
Anti-Freeze	2		4
Motor Oil	3		6

Table 3. ICEV and EV Primary and Maintenance Mass.
Note: EV maintenance mass is captured in replacement power packs not shown.
(Adapted from Sullivan and Hu, 1995 Table III)

Lead Acid EV Power Pack	Value[1]
Total Battery Pack Mass (kg)	Note 3
Lead & Lead Compounds (%)	Uniform distribution min. 15% max. 50%
Electrolyte (%)	Note 4
Polypropylene Case Material (%)	Uniform distribution min. 3% max. 8%
Ni-Cd EV Power Pack	**Value[2]**
Total Battery Pack Mass (kg)	Note 3
Nickel & Nickel hydroxide (%)	37%
Cadmium (%)	25%
Cobalt (%)	1%
Copper (%)	4%
KOH (%)	5%
LiOH (%)	1%
Water (%)	11%
Stainless Case and cover (%)	12%
Polypropylene Case Material (%)	3%
NiMH EV Power Pack	**Value[2]**
Total Battery Pack Mass	Note 3.
Nickel & Nickel hydroxide (%)	28%
Metal hydride (Al) (%)	13%
Polypropylene Separators (%)	5%
KOH (%)	3%
Water (%)	6%
Stainless (%)	44%

Table 4. EV Power Pack Mass Composition.

Note 1: Lead acid EV power-pack data from Optima MSDS, 2000
Note 2: Ni-Cd and NiMH composition data from Cuenca *et al.*, 1999
Note 3: Calculated as: energy requirement/energy density * range
Note 4: Calculated as: 100% - Lead(%) - Lead Compounds(%) - Polypropylene Case Material(%)

Material Emission Factor Development

Once differences in the materials consumed were known, the next step was to find factors to estimate the lifecycle emissions and inputs caused by material

consumption. Table 5 summarizes the methodology used in developing emission and input factors for the model.

Data Availability	Confidence	Methodology
Single Point	High	Uniform ± 10%
	Low	Uniform ± 50%
Two Points	One High, One Poor	Triangular, Best as Most Likely
	Any Other	Uniform, Points as Bounds
Three Points	One High	Triangular, Best as Most Likely, Lowest as Lower Bound, Highest as Upper Bound
	Any Other	Uniform, High/low Points as min/max
> 5 Points	Any	Bootstrap
	High With a Good Basis for Distribution Justification	Applied Distribution Using Data to Derive Descriptive Statistics

Table 5. Logic Applied in Emission and Input Factor Development.

When a single emission factor was reported in the literature and the confidence in that factor was low, the uniform distribution was applied with a minimum and maximum value of ±50 percent of the reported factor as shown in Table 5. This approach avoids the situation of a zero emission on the lower bound and maintains the central tendency at the reported value. When the confidence in a single factor was judged high, the uniform distribution was applied with a minimum and maximum value of ±10 percent of the reported factor. A uniform distribution was applied because the uniform distribution expresses the lowest certainty.

When two equally credible factors were reported, they became the minimum and maximum bounds of the uniform distribution. When two factors were reported and there was no basis to apply a theoretical distribution, a triangular distribution was

applied with the value judged most credible assuming the role of most likely as well as an endpoint.

When three factors were reported and there was no basis to apply a theoretical distribution, a triangular distribution was applied with the value judged most credible assuming the role of most likely. When the credibility of all the factors was judged equal, the minimum and maximum values were used for the minimum and maximum bounds of the uniform distribution.

When over five values of a parameter were available, and in the absence of a theoretical distribution, the individual values of the data were "bootstrapped" in the model; in other words the values were assigned a probability equal to their relative occurrence (Copeland *et al.*, 1992: 276). When the confidence in the values was high and a good basis for a theoretical distribution existed, the data points were used to develop the parameters of the distribution and the appropriate distribution was modeled.

These assumptions were modeled and the sensitivity of each variable was evaluated. If the sensitivity analysis revealed that the variability of a factor was "significant" in the overall lifecycle emissions or inputs, that factor was revisited to assure that the assumed distribution was realistic.

The methodology used in the development of the emissions and input factors for the model was admittedly subjective. Some emissions and inputs are well known while others are not well characterized. For example, the energy requirement for

aluminum processing is well understood, as companies must pay for the energy they consume in the form of electricity or some other fuel. Consequently, aluminum manufacturers are motivated to gather and maintain energy data for economic reasons. This data may then be available to researchers, unless it is protected due to the sensitive nature of the data. Other emission or input factors are not well known. PM_{10} emissions from bauxite mining, for example, are not well understood partly because there is little motivation for mining companies to monitor PM_{10} emissions and because PM_{10} emissions are highly variable. In fact, from a legal or regulatory perspective, there may be a disadvantage to tracking some emissions. When companies do not publish emission or input data, then data may come from organizations like the U.S. EPA.

The emission and input factors and distributions used by the model are shown in the following tables. Some of the sources used to construct the distributions for each variable were the EPA AP-42 database, other life cycle studies, and the Green Design Initiative Economic Input-Output Life Cycle Assessment (EIOLCA) Model at Carnegie Mellon University.

		Aluminum			Steel			Plastics		
Row #	Parameter	Assumed Distribution		Ref.	Assumed Distribution		Ref.	Assumed Distribution		Ref.
1	Coal Energy (MJ/1000kg)	46% of total fossil energy		f,i	72% of total energy		h	18% of total energy		h
2	Natural Gas Energy (MJ/1000kg)	31% of total fossil energy		f,i	23% of total energy		h	60% of total energy		h
3	Petroleum Energy (MJ/1000kg)	20% of total fossil energy		f,i	3% of total energy		h	20% of total energy		h
4	Non-Fossil Energy (MJ/1000kg)	70% of total energy		l	2% of total energy		h	2% of total energy		h
5	Total Energy (MJ/1000kg)		Min: 86,736 Max: 106,011	f,i,l		Min: 52,000 Max: 65,000 Likely: 58,500	h		56,000	h
6	Water Intake (liters/1000kg)		Min: 11,689 Max: 44,811 Likely: 11,689	f,i,l		Min: 109,967 Max: 134,404	i,l		91,308	f,g
7	Sulfur oxides (SOx) (g/kg)		Min: 41.0 Max: 43.7	f,i,l		Min: 5.8 Max: 6.8	e,i,l		5.6	f,g
8	Carbon Monoxide (CO) (g/kg)		Min: 28.0 Max: 51.0	f,i,l		Min: 13.6 Max: 23.0	e,i,l		4.6	f,g
9	Nitrogen oxides (NOx) (g/kg)		Min: 19.7 Max: 23.0	l		Min: 2.7 Max: 4.16	e,i,l		5.0	f,g
10	Volatile Organic Compounds (VOCs) (g/kg)		Min: 4.1 Max: 5.1	f,i		Min: 0.9 Max: 3.30 Likely: 3.30	e,i,l		Min: 2.4 Max: 4.8	h,j,l
11	Lead (g/kg)		Min: 0.07 Max: 0.08	f,i		Min: .005 Max: .0069	b,f,i		0.0013	f,g
12	PM_{10} (g/kg)		Min: 3.9 Max: 17.0 Likely: 17.0	f,i,l		Min: 0.5 Max: 0.77	b,f,i		0.5	f,g
13	Carbon Dioxide (g/kg)		Min: 5,721 Max: 6,467 Likely: 6,467	f,i,l		Min: 1,955 Max: 2,977	e,f,i		1,773	f,g
14	CH4 (gCO_2E/kg)		Min: 1.0 Max: 2.0	f,i,l		Min: 0.1 Max: 0.5	e,f,i		0.6	f,g
15	N2O (gCO_2E/kg)		Min: 51.3 Max: 61.2	f,i		12.1	f,i		14.5	f,g
16	CFCs (gCO_2E/kg)		Min: 15.3 Max: 18.7	f,i		1.2	f,i		38.5	f,g
17	CF_4 (gCO_2E/kg)		Min: 1.17 Max: 1.43	k	Assumed Not Significant			Assumed Not Significant		

Uniform distribution bounded on both ends by values in the literature.	Uniform distribution assigned bounds of ± 50% of the mean value given in the literature
Triangular distribution, location of the top point indicates which value is given "likely" status.	Uniform distribution assigned bounds of ± 10% of the mean value given in the literature.
EV Electric Vehicle	ICEV Internal Combustion Engine Vehicle

Table 6. Emissions Assumptions Related to Material Acquisition and Processing for Vehicle Manufacture.

		Copper			Sulfuric Acid			Lead		
Row #	Parameter	Assumed Distribution		Ref.	Assumed Distribution		Ref.	Assumed Distribution		Ref.
18	Coal Energy (MJ/1000kg)	40% of total energy		f,i	Assumed Not Significant			40% of total energy		f,i
19	Natural Gas Energy (MJ/1000kg)	27% of total energy		f,i	Assumed Not Significant			27% of total energy		f,i
20	Petroleum Energy (MJ/1000kg)	31% of total energy		f,i	Assumed Not Significant			31% of total energy		f,i
21	Non-Fossil Energy (MJ/1000kg)	2% of total energy		f,i	Assumed Not Significant			2% of total energy		f,i
22	Total Energy (MJ/1000kg)		42,380	f,i	Assumed Not Significant				42,380	f,i
23	Water Intake (liters/1000kg)		67,190	f,i	Assumed Not Significant				67,190	f,i
24	Sulfur oxides (SOx) (g/kg)		33.5	f,i		Min: 0.01 Max: 96.0 Likely: 7.0	c		45.0	c
25	Carbon Monoxide (CO) (g/kg)		14.6	f,i	Assumed Not Significant				36.0	c
26	Nitrogen oxides (NOx) (g/kg)		11.5	f,i		0.008	c		5.2	d
27	Volatile Organic Compounds (VOCs) (g/kg)		3.1	f,i	Assumed Not Significant				6.2	f,i
28	Lead (g/kg)		0.041	f,i	Assumed Not Significant				Min: 0.01 Max: 20	a
29	PM_{10} (g/kg)		2.9	f,i	Assumed Not Significant				1.8	c
30	Carbon Dioxide (g/kg)		3,990	f,i	Assumed Not Significant				3,990	f,i
31	CH_4 (gCO_2E/kg)		1.8	f,i	Assumed Not Significant				1.8	f,i
32	N_2O (gCO_2E/kg)		33.4	f,i	Assumed Not Significant				33.4	f,i
33	CFCs (gCO_2E/kg)		6.9	f,i	Assumed Not Significant				6.9	f,i

Table 6. Continued.

		Nickel			Potassium		
Row #	Parameter	Assumed Distribution		Ref.	Assumed Distribution		Ref.
34	Coal Energy (MJ/1000kg)	40% of total energy		f,i	Assumed Not Significant		
35	Natural Gas Energy (MJ/1000kg)	27% of total energy		f,i	Assumed Not Significant		
36	Petroleum Energy (MJ/1000kg)	31% of total energy		f,i	Assumed Not Significant		
37	Non-Fossil Energy (MJ/1000kg)	2% of total energy		f,i	Assumed Not Significant		
38	Total Energy MJ/1000kg)		42,380	f,i	Assumed Not Significant		
39	Water Intake (liters/1000kg)		67,190	f,i	Assumed Not Significant		
40	Sulfur oxides (SOx) (g/kg)		Min: 0.48 Max: 120	c	Assumed Not Significant		
41	Carbon Monoxide (CO) (g/kg)		14.6	f,i	Assumed Not Significant		
42	Nitrogen oxides (NOx) (g/kg)		Min: .006 Max: .64	c	Assumed Not Significant		
43	Volatile Organic Compounds (VOCs) (g/kg)		Min: .2 Max: .36	c	Assumed Not Significant		
44	Lead (g/kg)		Min: .07 Max: .08	f,m	Assumed Not Significant		
45	PM_{10} (g/kg)		Min: 3.9 Max: 17.0 Likely: 17.0	l,f,m		5.36	c
46	Carbon Dioxide (g/kg)		3,990	f,m	Assumed Not Significant		
47	CH_4 (gCO_2E/kg)		1.8	f,m	Assumed Not Significant		
48	N_2O (gCO_2E/kg)		33.4	f,m	Assumed Not Significant		
49	CFCs (gCO_2E/kg)		6.9	f,m	Assumed Not Significant		

a	Allen, David. Letters, Science, 269: 11 August 1995.	g	The Society of the Plastics Industry Total 1994 production http://www.plasticsindustry.org/ 1999
b	EPA Office of Compliance Sector Notebook Project Profile of the Iron and Steel Industry 1995	h	Stodlsky, F., A. Vyas, R. Cuenca, L. Gaines, "Life-Cycle Energy Savings Potential from Aluminum-Intensive Vehicles." Conference Paper, 1995
c	Factor Information Retrieval (FIRE) Database EPA. 1995. Section 12.15, Storage Battery Production. Compilation of Air Pollutant Emission Factors	j	Wang, Michael, "Greenhouse gas, Regulated Emissions, and Energy Use in Transportation (GREET)," Argonne National Laboratory January 2000
d	Factor Information Retrieval (FIRE) Database EPA. 1995. Emission factor based on one State value.	k	Weston, Ralph E. "Possible Greenhouse Effects of Tetrafluromethane and Carbon Dioxide Emitted from Aluminum Production," Atmospheric Environment, 1996.
e	Forintek Canada Corp. and Wayne B. Trusty & Associates Limited. "Building Materials in the Context of Sustainable Development: Phase II Summary Report"	l	Weston Roy F., "Life Cycle Inventory Report for the North American Aluminum Industry Executive Summary" The Aluminum Association, 1998
f	Green Design Initiative "Economic Input-Output Life Cycle Assessment model," 2000, Carnegie Mellon University.	m	U.S. Bureau of the Census, Manufacturing Profiles: 1994, MP/94, U.S. Government Printing Office, Washington, DC 1996.

Table 6. Continued.

Row #	Parameter	Electricity Generation: Assumed Distribution		Ref.	Gasoline Production: Assumed Distribution		Ref.	ICEV in-use Emissions: Assumed Distribution		Ref.
50	Coal		283 (g/kWh)	f	30% of total energy		1	N/A		
51	Natural Gas		22 (g/kWh)	f	21% of total energy		1	N/A		
52	Petroleum		5.99 (g/kWh)	f	44% of total energy		1	N/A		
53	Non-Fossil Energy (MJ/1000kg)	31.17 % of total energy		f	5% of total energy		1	N/A		
54	Total Energy (MJ/1000kg)	N/A				10,062	h	N/A		
55	Water		1.79 (l/kWh)	f		7.320 (l/kg)	1	N/A		
56	Sulfur Oxides (SOx)		3.64 (g/kWh)	f		0.932 (g/kg)	1		0.031 (g/km)	1
57	Carbon Monoxide (CO)		0.118 (g/kWh)	f		1.118 (g/kg)	1		Mean: 0.045 (kg/kg fuel) Var: 0.0089	c,f
58	Nitrogen Oxides (NOx)		1.72 (g/kWh)	f		1.546 (g/kg)	1		Mean: 0.005396 (kg/kg fuel) Var: 0.0000786	c,f
59	Volatile Organic Compounds (VOCs)		0.00907 (g/kWh)	f		0.728 (g/kg)	1		Mean: 0.0043 (kg/kg fuel) Var: 0.000065	c,f
60	Lead		0.0000186 (g/kWh)	f	Assumed Not Significant			Assumed Not Significant		
61	PM_{10}		0.0843 (g/kWh)	f		0.147 (g/kg)	1		0.0075 (g/km)	1
62	Carbon Dioxide		648.0 (g/kWh)	f		700 (gCO_2E/kg)	1		Mean: 3.06 (kg/kg fuel) Var: 0.03	c,f
63	Methane		1.02 (g/kWh)	f		107 (gCO_2E/kg)	1	Included in VOC		
64	Nitrous Oxide		0.00535 (g/kWh)	f		2.74 (gCO_2E/kg)	1	Included in NOx		

Uniform distribution assigned bounds of ± 10% of the mean value given in the literature.
Gamma distribution with parameters determined from real-world data.
Uniform distribution assigned bounds of ± 50% of the mean value given in the literature

EV	Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
a	AFV Database Alternative Fuels Data Center
b	Cuenca R.M., L.L. Gaines, and A.D. Vyas. "Evaluation of Electric Vehicle Production and Operating Costs." Argonne National Laboratory, Center for Transportation Research, Energy Systems Division, November 1999.
c	Gary A. Bishop, Sajal S. Pokharel and Donald H. Stedman, "On-Road Remote Sensing of Automobile Emissions in the Phoenix Area: Year 1" sensor data, November 2000
d	Lave, Lester B., Chris T. Hendrickson, and Frances C. McMichael. "Environmental Implications of Electric Cars," Science, 268: 19 May 1995.
e	Ming, Shaw-Pin, "Factors Associated with Aggregated Car Vehicle-scraping Rate in the United States: 1966-1992," Oak Ridge National Laboratory, Oak Ridge TN, January 1995.
f	Overly, Jonathan. "United States Electrical Energy Grid Life-Cycle Inventory Approach and Data." Report to U.S. Environmental Protection Agency, Dipti Singh, 25 June 1999.

Table 7. Emissions Assumptions Related to Vehicle Operation.

		EV Assumptions			ICEV Assumptions		
Row #	Property	Assumed Distribution		Ref.	Assumed Distribution		Ref.
65	Vehicle Energy Requirement (Wh/km)		Min: 150 Max: 528 Likely: 377	d,m,a,i	N/A		
66	Lead Acid Battery Lifetime (km)		Min: 30,000 Max: 42,000	d,k	N/A		
67	Ni-Cd Battery Lifetime (km)		Min: 93,200 Max: 108,800	k	N/A		
68	NiMH Battery Lifetime (km)		Min: 82,000 Max: 94,000	k	N/A		
69	Lead Acid Battery Energy Density (Wh/kg)		Min: 18 Max: 45	d,m,b	N/A		
70	Ni-Cd Battery Energy Density (Wh/kg)		Min: 55 Max: 57	b,m	N/A		
71	NiMH Battery Energy Density (Wh/kg)		Min: 70 Max: 80	g,b	N/A		
72	Lead Acid EV Range (km/charge)		Range: 64-126	a	N/A		
73	Ni-Cd EV Range (km/charge)		Min: 139 Max: 188	a	N/A		
74	NiMH EV Range (km/charge)		Range: 104-263	a	N/A		
75	Powergrid Transmission Efficiency (%)		Min: 92% Max: 99%	m	N/A		
76	Battery Discharge Efficiency (%)		Min: 75% Max: 95%	m	N/A		
77	Battery Charging Efficiency (%)		Min: 80% Max: 99% Likely: 80%	m	N/A		
78	Vehicle Life (km)		Range: 24,000 – 470,900	e,j		Range: 24,000 – 470,900	e,j
79	Vehicle Fuel Efficiency (km/kg fuel)	N/A				Min: 8.49 (20 mpg) Most Likely: 9.76(23 mpg) Max: 12.31 (29 mpg)	i

Uniform distribution bounded on both ends by values in the literature.	Triangular distribution, location of the top point indicates which value is given "most likely" status.
Discrete distribution constructed from data in the literature.	Data directly "boot strapped" into the model.

g	Ovshinsky, S.R., M.A. Fetcenko, and J. Ross. "A Nickel Metal Hydride Battery for Electric Vehicles" Science, 260: 9 April 1993.
h	Sheehan, John, Vince Camobreco, James Duffield, Michael Graboski, and Housein Shapouri. "An Overview of Biodiesel and Petroleum Diesel Life Cycles," National Renewable Energy Laboratory Golden, 1998
i	Sullivan, John L., and J. Hu. Life Cycle Energy Analysis for Automobiles. Society of Automotive Engineers report number 951829: 1995.
j	U.S. Department of Transportation, Federal Highway Administration, 1995 Nationwide Personal Transportation Survey
k	Vyas, Anant D., Henry K. Ng, Danilo J. Santini, John L. Anderson. "Batteries for Electric Drive Vehicles: Evaluation of Future Characteristics and Costs through a Delphi Study," SAE International Spring Fuels and Lubricants Meeting, May 5-7, 1997
l	Wang, Michael, "Greenhouse gas, Regulated Emissions, and Energy Use in Transportation (GREET)," Version 1.5a, Argonne National Laboratory January 2000
m	Wang, Quanlu, and Mark A. DeLuchi. "Impacts of Electric Vehicles on Primary Energy Consumption and Petroleum Displacement," Energy, 17-4: 1992
n	Zhang, Yi, Gary A. Bishop, Donald H. Stedman "Automobile Emissions Are Statistically Gamma-Distributed", Environmental Science and Technology, Volume 28, Number 7, 1994

Table 7. Continued.

The EIOLCA model allows the estimation of the overall environmental impacts from commodity production in the United States by cost (eiolca.com, November 2000). In developing the emission and input factor distributions used in this research, the total dollar value of production for a sector of interest, for example the plastics industry, was obtained and input into the EIOLCA model. The EIOLCA model then yielded an estimate of the total inputs and emissions for the plastics industry for that year. The total resource input and pollution output amounts were then divided by the total mass output of the plastics sector to yield a pollutant or input per unit mass-produced factor that was used in the model. When these factors were the only ones available, the lowest level of certainty was applied, a uniform distribution bounded by ±50 percent.

Of course, one could debate that the methodology applied in Table 5 is somewhat arbitrary as no theoretical justification is given for the bounds of the uniform distribution described and the notions of "high" and "low" confidence are ill defined. However, expressing the uncertainty inherent in emission and input factors in this way is a better approximation of reality than simply assigning a point estimate. However the debate about the "precise extent of uncertainty reveal the bankruptcy of the practice of expressing risks… (or emission factors used to calculate risks) via point estimates that admit no possible imprecision" (Finkel, 1994:382).

Lifetime Driving Distance Assumptions

The total lifecycle driving distance PDF was developed by summing the average yearly distance driven over the assumed life span of the vehicle. The average annual distance driven for light vehicles is shown in Figure 3 and declines over the life of the vehicle (Erlbaum, 1999:16). The nationwide fitted data was used in the model. In other words, people drive old cars less than they drive new cars. Figure 3 only provides data for 14 years so for vehicle lives beyond 14 years a constant value of 6,500 miles/year (10,400km) is assumed as reported in the 1995 NPTS Summary of Travel Trends for vehicles of this age (U.S. Department of Transportation, 1995).

The annual vehicle-scraping rate as reported by Miaou for the 1990 model year automobile is shown in Figure 4 (Miaou, 1995). This cumulative distribution function (CDF) represents the cumulative probability that a vehicle will have been scrapped by a given year of its lifetime. Miaou's data only accounts for 20 years of life, beyond that the formulation assumes a constant vehicle-scraping rate of 22 percent per year as given for year 20.

The annual vehicle-scrapping rate (Figure 4) was combined with the average annual distance driven (Figure 3) to determine the total vehicle lifetime distance driven. The vehicle total life cycle distance PDF used in the model is shown in Figure 5. All vehicles were assumed to survive until the end of year 1, P(scrap at 1 yr.) = 0, and the maximum life was truncated at 34 years, P(scrap at 34 yr.) = 1. This distribution represents the probability that a randomly selected vehicle will have gone

the distance on the x-axis in its entire lifetime. This distribution was used in the model to establish total life cycle driving distance for both the EV and ICEV.

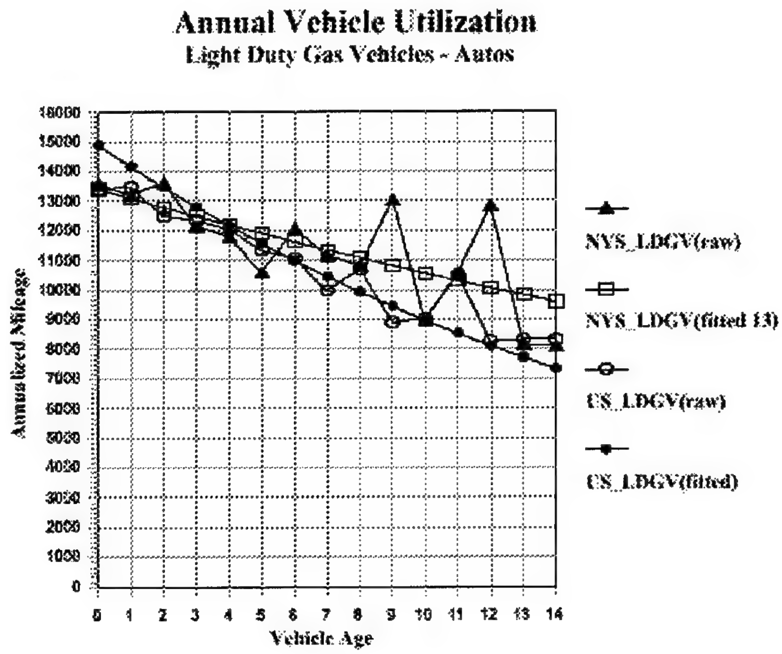

Figure 3. Light Duty Vehicle Average Annual Mileage. (Erlbaum, 1999:16)
NYS_LDGV: New York State Light Duty Gas Vehicle (Automobiles)
US_LDGV: Nationwide United States Light Duty Gas Vehicle (Automobiles)
raw: Raw data from vehicle registration information
fitted: Linear fit of raw data

Use Phase Emission Assumptions

During the use phase of the automobile life cycle, external energy is input to the vehicle in order to drive it. All inputs and emissions from the resource extraction and processing of electricity for the EV and gasoline for the ICEV are included in the use phase of the model. The energy generation processes for both vehicle types are well

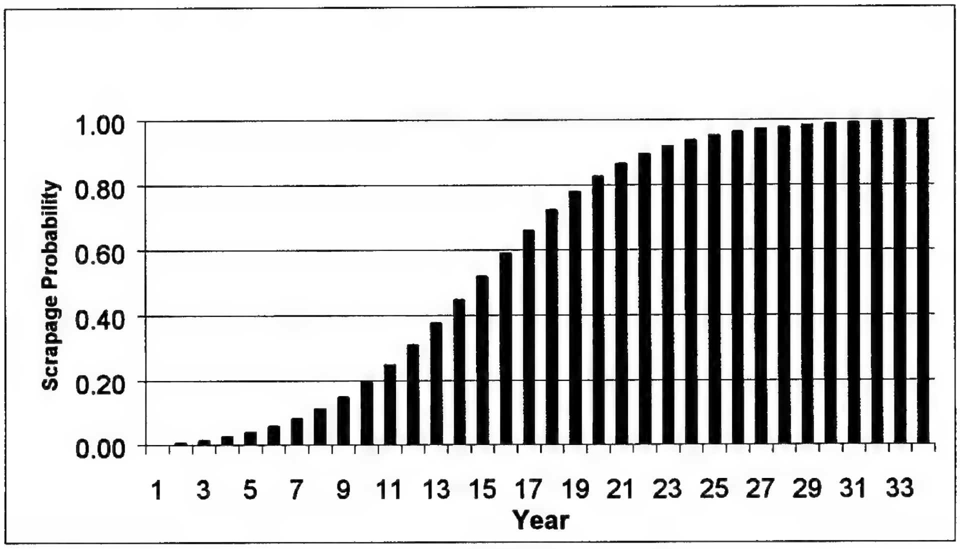

Figure 4. Cumulative Vehicle Vehicle-scraping Probability.

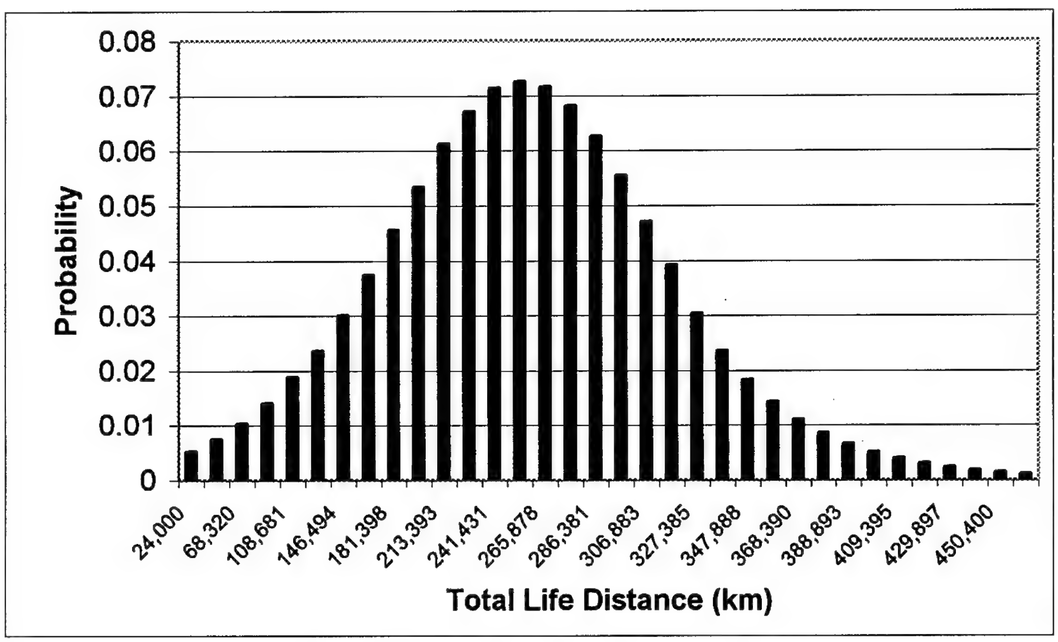

Figure 5. Vehicle Total Life Distance PDF.

characterized and the emission factors applied in the model formulation have been previously discussed.

The consequences of ICEV fuel combustion have been discussed earlier in this report. ICEV emissions have been greatly reduced by pollution control devices (Utell, 1994: 160). However, the possibility for very high emissions still exists if the ICEV's pollution control devices fail or are deliberately tampered with and the vehicle becomes a high emitter. High emitters contribute a disproportionate amount of the total on-road vehicle pollution. In one study, Beaton reports that 7 percent of the automobiles accounted for 50 percent of the pollutants emitted (Beaton *et al.*, 1995:991). These gross polluters are not all old vehicles and not all old vehicles become gross polluters as assumed by most legislation (Beaton *et al.*, 1995:992). While a correlation between age and pollution does exist, in the same study Beaton reports that the dirtiest 20 percent of new cars emitted more pollution than the cleanest 40 percent of vehicles from any model year (Beaton *et al.*, 1995:268).

The possibility that a vehicle may become a high emitter was modeled in this research by assigning the ICEV in-use emissions a gamma distribution as recommended by Zhang (Zhang *et al.*, 1994). The skewed nature of the gamma distribution indicates that while most vehicles will have good emissions, a few will be extreme outliers and can dominate the overall emissions profile. The parameters of the gamma distributions used by the model were developed from real-world samples of over 20,000 vehicles reported by Bishop (Bishop, 2000). The extreme high values of the distribution were not allowed to go to the theoretical upper limit of infinity, but were truncated to a reasonable maximum given the combustion reaction. The

different emissions are also correlated based on the Bishop data as shown in Table 8. There is a weak correlation between age and high emissions, and between emissions. For example, high CO means low CO_2, and an older vehicle tends to correlate with high VOC, CO, and NO emissions.

Correlation Between Emissions Data					
Variable	**Vehicle Age (Years)**	**kg CO_2/kg Fuel**	**kg NO/kg Fuel**	**kg VOC/kg Fuel**	**kg CO/kg Fuel**
Vehicle Age (Years)	-	-.3390	.3307	.2213	-.3284
Kg CO_2/kg Fuel	-.3390	-	.0013	-.4657	-.9916
Kg NO/kg Fuel	.3307	.0013	-	.0531	-.0101
Kg VOC/kg Fuel	.2213	-.4657	.0531	-	.3654
Kg CO/kg Fuel	.3284	-.9916	-.0101	.3654	-

Table 8. Correlation of ICEV In-Use Pollutant Emissions

Other Vehicle Property Assumptions

Tying together the use phase emissions and inputs with the length of the use phase is the vehicle efficiency or energy requirements per unit activity. This is expressed as fuel efficiency for the ICEV, in kg fuel per km driven and vehicle energy required in watt-hours per km driven for the EV. A vital set of parameters for the EV are the transfer efficiencies for the movement of electricity from the power plant to the charging station, from the charging station to the batteries and finally from the batteries to the vehicle motor and transmission system. These parameters are shown in Table 7, rows 59-61.

Drivability Assumptions

One aspect of the EV not modeled is its drivability. EV range per charge is taken into account; however, acceleration, time to recharge, and safety are not

evaluated in this research. These are important marketability features that influence public acceptance of EVs and EV emissions. Another facet of performance is the interaction of the EV with other vehicles. A slow moving, poorly accelerating EV could cause congestion as it interacts with ICEVs and actually result in higher aggregate emissions. Stedman summarizes this notion:

> "I have always contended that battery electric vehicles in realistic use will sooner or later become slugs (heavy and low power). They will then crawl up the many hills in LA actually causing the conventional vehicles behind them to drive much slower. At low speeds slower driving is almost linearly related to higher pollutant emissions per mile, so a realistic fleet with a small fraction of realistically maintained electric vehicles will actually increase rather than decrease on-road emissions... Needless to say this piece of realism is in no one's models" (Stedman, personal communication).

IV. Results

Model Output

The model output is given in the following paragraphs. Simulation output is presented in box-and-whiskers plots constructed from the percentiles of the output data. The ends of the box represent the 25^{th} and 75^{th} percentile, the line within the box is the 50^{th} percentile, and the "whiskers" are the observed values at the 2.5^{th} and 97.5^{th} percentile. The 0^{th} and 100^{th} percentiles were not used due to considerations of scale, when they were used the box became to small to see in some cases so the results are truncated in the figures. Any skewness in the resulting distribution is represented by the distance between the 50^{th} percentile versus the other percentiles. The raw model output only represents a difference between the EV platforms and the ICEV. An estimate of EV emissions is provided by comparing the model output to the benchmark deterministic study results as published by Sullivan and others (Sullivan *et al.*, 1998).

Total Energy

The lifecycle energy consumed per km traveled was generally lower for all EV platforms as shown in Figure 6. The model output indicates that there is a 66.18 percent chance that the lead acid EV total life cycle energy required will be less than the ICEV. Conversely, there is a 33.82 percent chance that the lead acid EV will consume more energy than the ICEV. Table 9 shows that the variables most impacting the total energy consumed are the efficiencies of the ICEV and EV during the use phase of their lifecycles. As discussed earlier, the ICEV has relatively poor operational efficiency but it is still practical to operate due to gasoline's extremely high energy density. The EV lifecycle enjoys superior efficiency because the power plants it relies on are able to continuously operate at near peak efficiency.

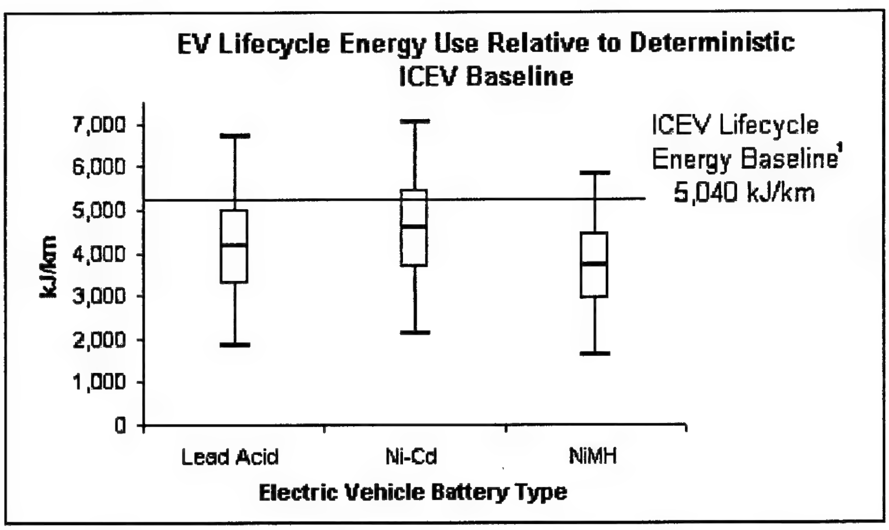

Figure 6. Lifecycle Energy Difference Relative to Deterministic Internal Combustion Engine Vehicle (ICEV) Baseline
[1]Baseline value from Sullivan *et al.*, 1998 total lifecycle energy use divided by a 120,000-mile lifecycle driving distance

Tables 6-7 Row #	Input Variable	Electric Vehicle (EV) Type		
		Lead Acid	Ni-Cd	NiMH
65	Vehicle Energy Requirement (Wh/km)	-0.82	-0.87	-0.84
79	ICEV Fuel Efficiency (km/kg)	-0.32	-0.30	-0.36
76	Battery Efficiency (%)	0.19	0.18	0.21
77	Charger Efficiency (%)	0.15	0.15	0.17
75	Powergrid Transmission Efficiency (%)	0.05	0.06	0.06
69	Lead Acid Battery Energy Density (Wh/kg)	0.19	0.01	0.01
22	Lead Production Total Energy Input (MJ/1000kg))	-0.17	0.01	0.02
38	Nickel Production Total Energy Input (MJ/1000kg))	0.02	-0.14	-0.01
5	Plastic Production Total Energy Input (MJ/1000kg))	-0.03	-0.03	-0.02
Table 4	Lead Battery Lead Composition (%)	0.04	-0.01	0.00
73	Ni-Cd EV Assumed Range (km/charge)	0.00	-0.04	0.00
74	NiMH EV Assumed Range (km/charge)	0.00	0.00	-0.07
72	Lead Acid EV Assumed Range (km/charge)	-0.14	0.01	0.01
66	Lead Acid Battery Life (km)	0.04	0.07	0.01
50	Electricity Coal Input (g/kWh)	-0.13	-0.12	-0.14
51	Electricity Natural Gas Input (g/kWh)	-0.04	-0.04	-0.04
50	Coal Energy Input for Gasoline Manufacturing (MJ/1000kg)	0.02	0.03	0.03
52	Gasoline Manufacturing Petroleum Energy Input (MJ/1000kg)	0.03	0.03	0.03

Table 9. Correlation of Lifecycle Energy Difference Output to Significant Input Variables

The median savings for the three platforms are 893 kJ/km for the Lead Acid EV, 453 kJ/km for the Ni-Cd EV, and 1,340 kJ/km for the NiMH EV. Sullivan estimates a total lifecycle energy input requirement for the ICEV of 5,040 kJ/km assuming a 120,000-mile lifetime (Sullivan *et al.*, 1998:12). Therefore, the median result for each platform represents an improvement in energy efficiency of 17 percent for the Lead Acid EV, 9 percent for the Ni-Cd EV, and 26 percent for the NiMH EV.

The change in the composition of energy sources is more significant to the stated goal of improved energy security than the change in the amount of lifecycle energy consumed. Use of the EV shifts the primary energy source from petroleum to coal and a larger fraction of non-fossil energy (hydroelectric, nuclear) is consumed. Figure 7 shows the modeled portion of the total lifecycle energy broken out by source. Because this research focuses on the differences between the ICEV and the three EVs, this is not a comprehensive analysis of the total energy used. However, it is assumed that the missing portion of lifecycle energy is identical across the four options.

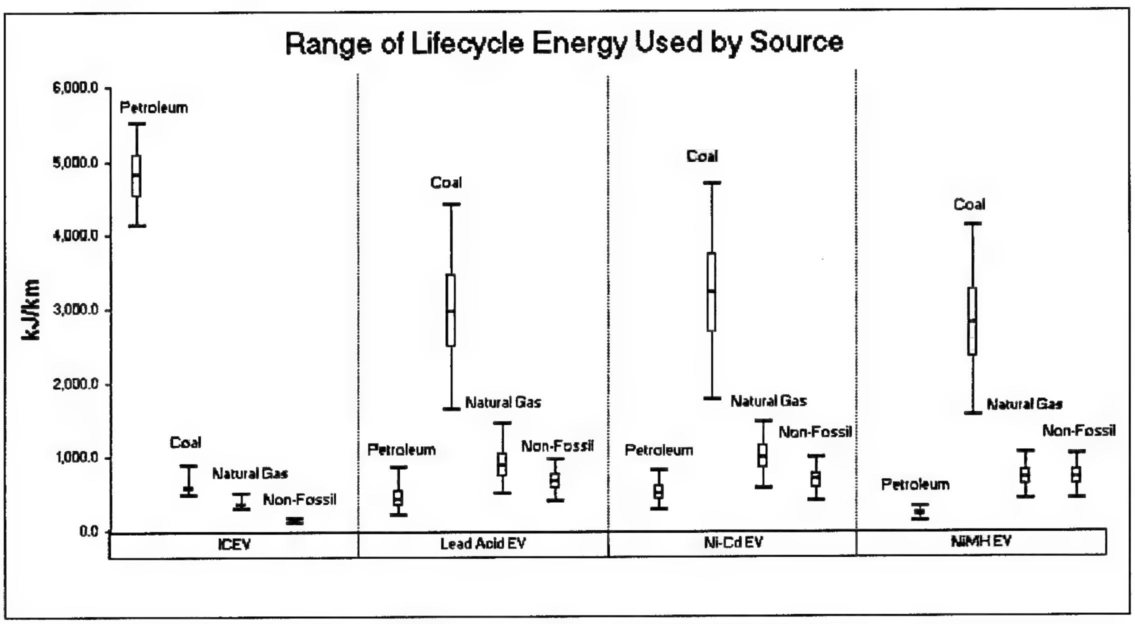

Figure 7. Range of Lifecycle Energy Sources for the Modeled Portion of Vehicle Lifecycle Energy
ICEV = Internal Combustion Engine Vehicle
EV = Electric Vehicle

A greater portion of the energy consumed by the EV platforms goes into manufacture and maintenance than the ICEV as shown in Figure 8. This is caused by the

large maintenance mass required to replace EV power packs over the life of the vehicle. However, the use phase still dominates overall energy consumption.

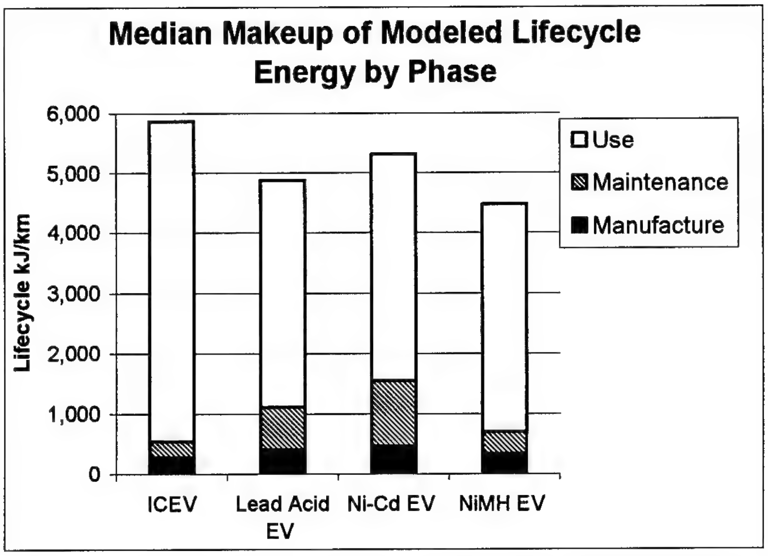

Figure 8. Median Lifecycle Energy Consumption by Source for the Modeled Portion of Vehicle Lifecycle Energy.
ICEV = Internal Combustion Engine Vehicle
EV = Electric Vehicle

CO_2 Equivalent

Figure 9 shows the expected CO_2 emissions resulting from a shift to the EV. Sullivan estimated total ICEV lifecycle CO_2 emissions at 307.7 g/km assuming a 120,000-mile lifetime (Sullivan, 1998:12). The model predicts there is a good possibility that CO_2 emissions will increase with the lead acid and Ni-Cd EVs and decrease with the NiMH EV. The EVs themselves emit no CO_2, but the interaction of the transmission, charger, and battery efficiencies combined with the EV energy requirement and CO_2 emissions from electricity generation cause them to emit a comparable amount of CO_2 per unit distance driven to ICEV. The manufacturing of power packs causes a

considerable increase in the quantity of nickel, lead, and copper processed, also resulting in significant emissions.

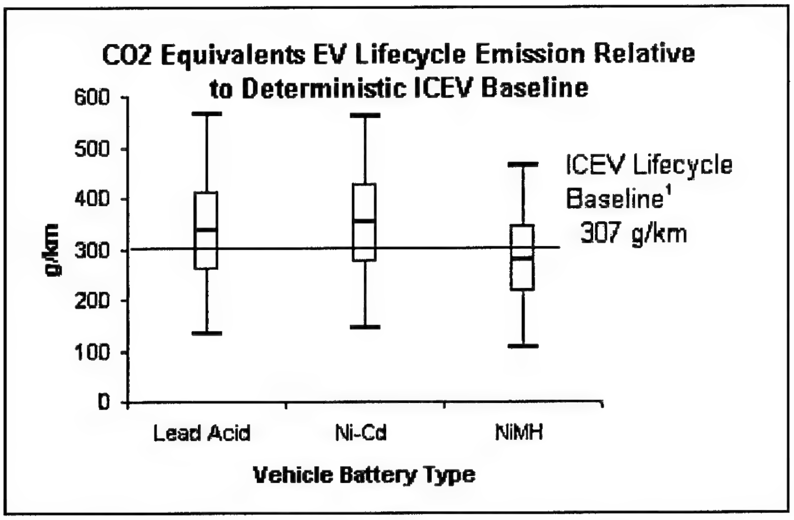

Figure 9. Electric Vehicle (EV) Lifecycle CO_2 Equivalents (CO_2E) Emission Difference Relative to Deterministic Internal Combustion Engine Vehicle (ICEV) Baseline
[1]Baseline value from Sullivan *et al.*, 1998 total lifecycle CO_2 emissions divided by a 120,000-mile lifecycle driving distance

Tables 6-7 Row #	Input Variable	Electric Vehicle Type		
		Lead Acid	Ni-Cd	NiMH
65	Vehicle Energy Requirement (Wh/km)	-0.81	-0.86	-0.83
79	ICEV Fuel Efficiency (km/kg fuel)	-0.24	-0.24	-0.29
62	Gasoline Production CO_2 Emission (g/kg)	0.20	0.19	0.23
69	Lead Acid Battery Energy Density (Wh/kg)	0.19	0.01	0.01
76	Battery Efficiency (%)	0.19	0.19	0.22
77	Charger Efficiency (%)	0.14	0.14	0.17
75	Powergrid Transmission Efficiency (%)	0.05	0.06	0.07
62	Electricity CO_2 Emission (g/kWh)	-0.18	-0.18	-0.20
30	Lead CO_2 Emission (g/kg)	-0.17	0.03	0.04
72	Lead Acid EV Range (km/charge)	-0.15	0.01	0.01
57	ICEV Use CO Emission (g/kg fuel burned)	-0.05	-0.05	-0.06
46	Nickel Production CO_2 Emission (kg/kg)	0.00	-0.12	-0.02
30	Copper Production CO_2 Emission (g/kg)	0.02	-0.08	0.02
66	Lead Acid Battery Life (km)	0.05	0.07	0.00

Table 10. Correlation of CO_2 Equivalent Emission Difference to Significant Input Variables

Equal or higher CO_2 emissions may seem like a disparity as CO_2 emission is usually associated with energy use and Figure 6 indicated a good possibility that energy used per km traveled would go down with a shift to the EV. This seeming disparity is explained by the fact that coal emits more CO_2 per unit energy generated than gasoline. Coal has a wide range of chemical compositions but generally contains less hydrogen per unit mass than gasoline. Coal emits approximately 24.1g carbon per MJ energy released. Contrast this to gasoline, which emits approximately 18.5g carbon per MJ energy released (Marland, 1983). Therefore, the shift from gasoline to coal as a primary source of energy could result in an increased lifecycle CO_2 emission as predicted by the model.

Criteria Pollutants

SOx

The shift in energy source from petroleum to coal and the increase in mining and mineral activity cause SOx emissions per km driven to be higher for each of the EV platforms as shown in Figure 10. The primary drivers in EV SOx emissions are SOx emissions from electricity and EV energy demand as shown in Table 11.

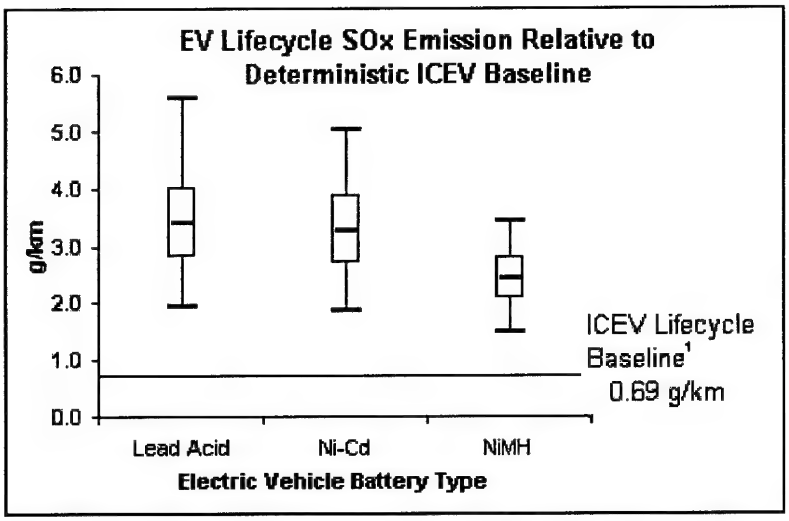

Figure 10. Electric Vehicle (EV) Lifecycle Sulfur Oxides (SOx) Emission Difference Relative to Deterministic Internal Combustion Engine Vehicle (ICEV) Baseline
[1]Baseline value from Sullivan *et al.*, 1998 total lifecycle SOx emissions
divided by a 120,000-mile lifecycle driving distance

Tables 6-7 Row #	Input Variable	Electric Vehicle (EV) Type		
		Lead Acid	Ni-Cd	NiMH
65	Vehicle Energy Requirement (Wh/km)	-0.77	-0.79	-0.88
76	Battery Discharge Efficiency (%)	0.14	0.13	0.23
75	Powergrid Transmission Efficiency (%)	0.04	0.05	0.07
77	Charger Efficiency (%)	0.10	0.10	0.17
74	NiMH Assumed Range (km/charge)	0.00	0.00	-0.06
72	Lead Acid EV Assumed Range (km/charge)	-0.26	0.02	0.01
69	Lead Acid Battery Energy Density (Wh/kg)	0.34	0.01	0.01
40	Nickel Production SOx Emission (g/kg)	0.00	-0.51	-0.16
56	Electricity Production SOx Emission (g/kg)	-0.11	-0.11	-0.19
24	Lead Production SOx Emission (g/kg)	-0.22	0.06	0.08
24	Sulfuric Acid Production SOx Emission (g/kg)	-0.17	0.04	0.07
24	Copper Production SOx Emission (g/kg)	-0.02	-0.13	-0.02
56	Gasoline Production SOx Emission (g/kg)	0.03	0.03	0.05
66	Lead Acid Battery Life (km)	0.09	0.08	-0.02
Table 4	Lead Battery Lead Composition (%)	0.08	-0.01	-0.01
73	Ni-Cd EV Assumed Range (km/charge)	0.00	-0.06	0.00

Table 11. Correlation of Lifecycle SOx Emission Difference Output to Significant Input Variables

A shift from the ICEV to the EV will cause SOx emissions to increase significantly. Sullivan estimates a total lifecycle SOx emission factor for the ICEV of 0.69 g/km assuming a 120,000-mile lifetime (Sullivan, 1998:12). A shift to the Lead Acid EV could result in a doubling of lifecycle SOx emissions.

CO

CO emissions are generally lower for each EV platform as shown in Figure 11. The very long negative tail is caused by ICEVs that become high emitters. Relative to Sullivan's estimated lifecycle emission the model actually predicts a negative value for CO emissions, this is of course impossible; a vehicle cannot have a negative emission. This aberration is caused by a fundamental difference in modeling philosophy between deterministic and stochastic modeling. The model constructed for this research allows

vehicles to become high emitters. If many vehicles are high emitters, then the EV will drastically lower aggregate CO emissions. If few vehicles are high emitters, as is the case when an effective inspection and maintenance program is in place, then the EV may actually result in deterioration in CO emissions. Inspection and maintenance programs may effectively address high emitting ICEVs but the EV is superior because they can never become high emitters.

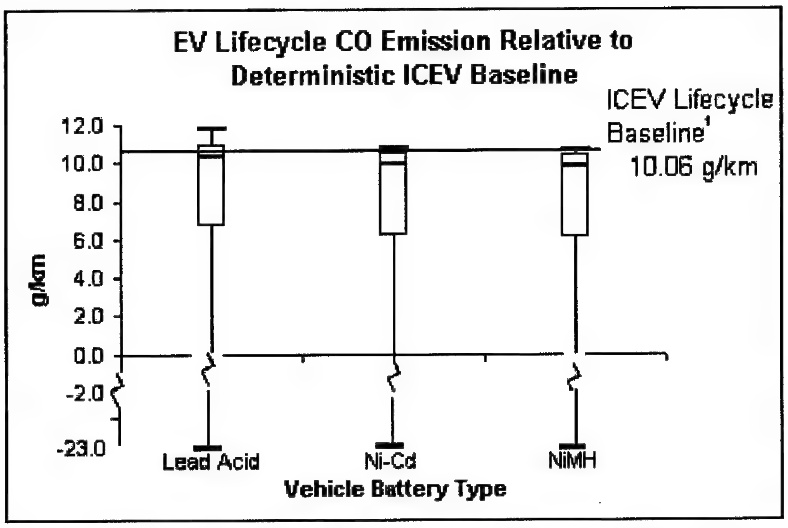

Figure 11. Electric Vehicle (EV) Lifecycle Carbon Monoxide (CO) Emissions Relative to Deterministic Internal Combustion Engine Vehicle (ICEV) Baseline
[1]Baseline value from Sullivan *et al.*, 1998 total lifecycle CO emissions divided by a 120,000-mile lifecycle driving distance

Another significant fact is that there exists a positive correlation between vehicle life and the CO difference indicating that the longer the vehicles are in operation the more positive the emission difference becomes. This is especially significant when evaluating model output. A model that assumes a fixed short vehicle life will tend to discount this emission difference and yield results more favorable to the ICEV.

Tables 6-7 Row #	Input Variable	Electric Vehicle Type		
		Lead Acid	Ni-Cd	NiMH
57	ICEV Use CO Emission (kg/kg fuel)	0.91	0.96	0.97
78	Vehicle Life (km)	0.27	0.30	0.30
65	Vehicle Energy Requirement (Wh/km)	-0.14	-0.11	-0.07
69	Lead Acid Battery Energy Density (Wh/kg)	0.14	-0.01	0.00
72	Lead Acid EV Assumed Range (km/charge)	-0.12	-0.01	-0.01
25	Lead Manufacturing CO Emission (g/kg)	-0.13	0.05	0.06
25	Copper Manufacturing CO Emission (g/kg)	0.00	-0.06	0.01

Table 12. Correlation of CO Emission Difference to Significant Input Variables

For the Ni-Cd and NiMH EVs, there is a significant decrease in CO emissions. GREET assigns a use phase emission factor for CO of 3.44 g/km to the ICEV (Wang, 2000). Sullivan estimates a total lifecycle CO emission rate for the ICEV at 10.06 g/km assuming a 120,000-mile lifetime (Sullivan, 1998:12).

NOx

NOx emissions are generally higher for the EV platforms than the ICEV as shown by Figure 12. Modern ICEV emission control devices do a good job of controlling NOx. When these systems fail, the vehicle becomes a high emitter. As with CO, the longer positive tails in Figure 12 show this. However, these tails are not as pronounced as the CO plot. The correlation factors in Table 13 indicate that NOx emissions from electricity production, combined with EV energy requirement and the associated delivery efficiencies, cause the EV CO emissions to become generally higher.

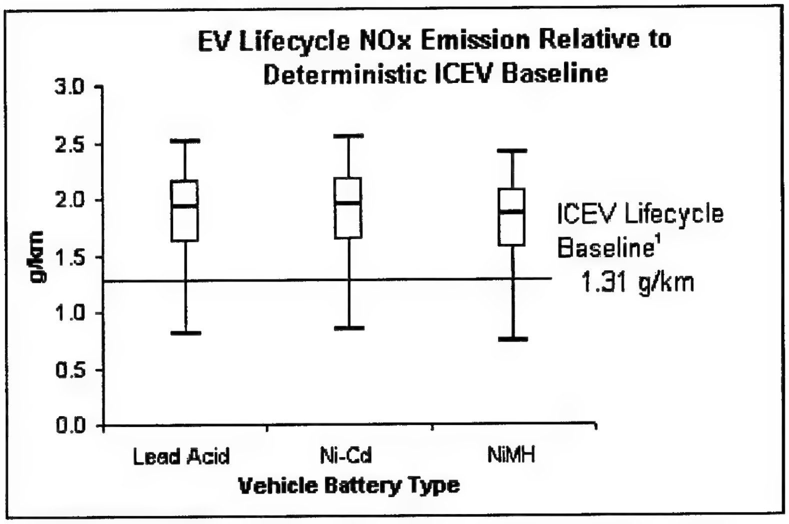

Figure 12. Electric Vehicle (EV) Lifecycle Nitrogen Oxides (NOx) Emissions Difference Relative to Deterministic Internal Combustion Engine Vehicle (ICEV) Baseline.
[1]Baseline value from Sullivan *et al.*, 1998 total lifecycle NOx emissions divided by a 120,000-mile lifecycle driving distance.

This is a significant increase in lifecycle NOx emission. GREET assigns a use phase emission factor of 0.171 g/km to the ICEV (Wang, 2000). Lave suggests a range for ICEV NOx emissions from 0.25 g/km to 0.81 g/km (Lave *et al.*, 1996, 403). Sullivan estimates a total lifecycle NOx emission for the ICEV at 1.31 g/km assuming a 120,000-mile lifetime (Sullivan, 1998:12). As shown in Figure 12, the model indicates that there is a high probability that a shift from the ICEV to the EV will increase aggregate NOx emissions.

Tables 6-7 Row #	Input Variable	Electric Vehicle (EV) Type		
		Lead Acid	Ni-Cd	NiMH
58	ICEV In Use NOx Emission (kg/kg fuel)	0.69	0.69	0.71
79	ICEV Fuel Efficiency (km/kg fuel)	-0.05	-0.05	-0.05
65	EV Energy Requirement (Wh/km)	-0.55	-0.56	-0.53
58	Electricity NOx Emission (g/kWh)	-0.13	-0.13	-0.13
58	Gasoline Production NOx Emission (g/kg)	0.13	0.12	0.13
78	Vehicle Life (km)	0.22	0.23	0.23
72	Lead Acid EV Range (km/charge)	-0.05	0.01	0.00
26	Lead NOx Emission (g/kg)	-0.05	0.02	0.02
26	Copper NOx Emission (g/kg)	-0.01	-0.09	-0.01
69	Lead Acid Battery Energy Density (Wh/kg)	0.08	0.01	0.01
77	Charger Efficiency (%)	0.11	0.11	0.12
76	Battery Efficiency (%)	0.15	0.15	0.16

Table 13. Correlation of NOx Emission Difference to Significant Input Variables.

VOC

VOC emissions are usually lower for the EV platforms as shown in Figure 13. VOC emissions are lower because a relatively small amount of liquid fuel is involved in the EV lifecycles.

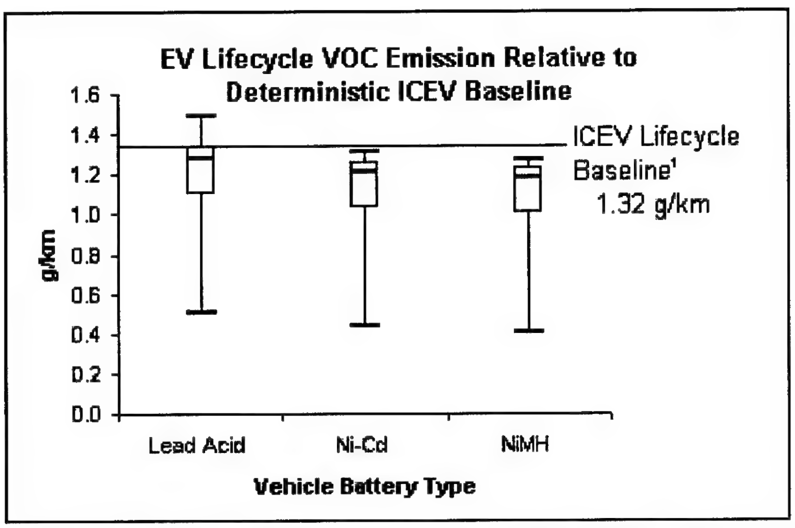

Figure 13. Electric Vehicle (EV) Lifecycle Volatile Organic Carbons (VOC) Emissions Difference Relative to Deterministic Internal Combustion Engine Vehicle (ICEV) Baseline
[1]Baseline value from Sullivan *et al.*, 1998 total lifecycle VOC emissions divided by a 120,000-mile lifecycle driving distance.

The Lead Acid EV does actually worsen VOC emissions part of the time when a high power pack mass is chosen due to lead production VOC emissions. ICEVs are responsible for VOCs directly through incomplete combustion, evaporative emissions, and the transfer and storage of automotive fuels. EV energy is distributed via power-lines, eliminating the need for fuel distribution by truck. The ICEV use phase emissions dominate the VOC emission difference as shown by the high correlation factors in Table 14.

Tables 6-7 Row #	**Input Variable**	**Electric Vehicle (EV) Type**		
		Lead Acid	**Ni-Cd**	**NiMH**
59	ICEV in Use VOC Emission (kg/kg fuel)	0.83	0.92	0.92
65	Vehicle Energy Requirement (Wh/km)	-0.18	-0.11	-0.04
69	Lead Acid Battery Energy Density (Wh/kg)	0.21	-0.01	-0.01
72	Lead Acid EV Range (km/charge)	-0.16	0.01	0.01
79	ICEV Fuel Efficiency (km/kg fuel)	-0.07	-0.10	-0.10
Table 4	Lead Battery Lead Composition (%)	0.04	0.00	0.00
59	Gasoline Production VOC Emission (g/kg)	0.13	0.21	0.23
27	Lead Production VOC Emission (g/kg)	-0.19	0.06	0.07
27	Copper Production VOC Emission (g/kg)	-0.01	-0.10	-0.01
78	Vehicle Life (km)	0.17	0.19	0.19

Table 14. Correlation of VOC Emission Difference to Significant Input Variables

Lave gives a range for ICEV VOC emissions from 0.1875 g/km to 0.69 g/km (Lave *et al.*, 1996, 403). Sullivan estimated total ICEV lifecycle non-methane hydrocarbon emissions at 1.32 g/km assuming a 120,000-mile lifetime (Sullivan,1998:12). As shown in Figure 13, the model indicates that there is a high probability that a shift from the ICEV to the EV will decrease aggregate VOC emissions.

Lead

With the other emissions and inputs, the EV platforms shared the same general tendency relative to the ICEV. As Figure 14 shows, this is not the case with lead emissions. Here the lead-acid EV clearly has higher emissions than the ICEV, while the Ni-Cd and NiMH EVs are lower. As shown in Table 15, lead manufacturing causes this difference. This model does not characterize the lead emission by media (air, water etc.). Because lead is persistent in the environment, any emission should be weighed heavily.

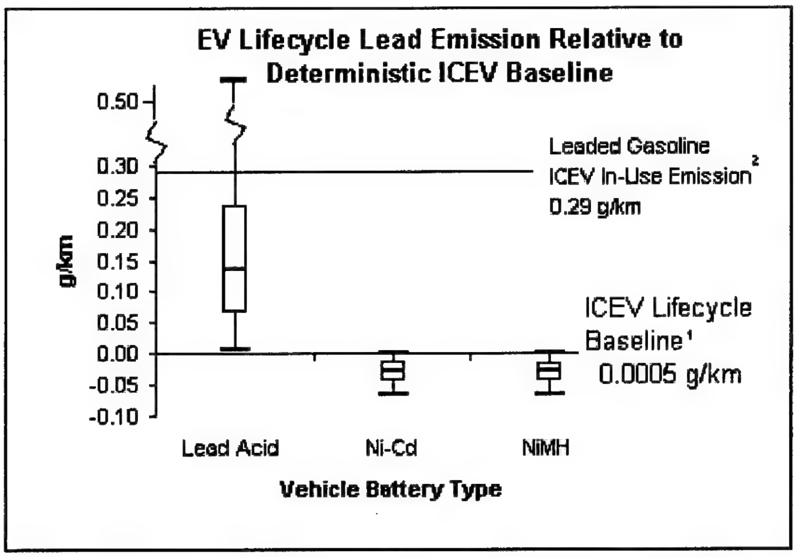

Figure 14. Electric Vehicle (EV) Lifecycle Lead Emissions Relative to Deterministic Internal Combustion Engine Vehicle (ICEV) Baseline
[1]Baseline value from Sullivan *et al.*, 1998 total lifecycle lead emissions divided by a 120,000-mile lifecycle driving distance
[2]Historical ICEV lead emissions when lead was an additive in gasoline as predicted by Lave and others 1996

Tables 6-7 Row #	Input Variable	Electric Vehicle (EV) Type		
		Lead Acid	Ni-Cd	NiMH
28	Lead Production Lead Emission (g/kg)	-0.80	0.97	0.97
69	Lead Acid Battery Energy Density (Wh/kg)	0.33	-0.01	-0.01
72	Lead Acid EV Range (km/charge)	-0.26	0.01	0.01
66	Lead Acid Battery Life (km)	0.08	-0.12	-0.13
65	Vehicle Energy Requirement (Wh/km)	-0.29	-0.02	0.00
Table 4	Lead Battery Lead Composition (%)	0.08	0.06	0.06

Table 15. Correlation of Lead Emission Difference to Significant Input Variables.

Because lead has been eliminated from gasoline in the U.S., emission models typically no longer estimate its emission with respect to ICEV operation. One estimate of ICEV lead emission, when lead was in use as a fuel additive, is given by Lave as 0.29 g/km (Lave *et al.*, 1996:403). Current ICEV lead emissions are estimated by Sullivan as 0.0005 g/km (Sullivan, 1998:12).

As discussed earlier, there has been great debate over the appropriate factor to apply for lead emissions. This research, therefore, used a wide range on lead emissions, resulting in great variability in the output. Despite this variability, it is clear that a shift from the ICEV to the Lead Acid EV would result in a significant increase (as much as three orders of magnitude) in lead emissions. Another interesting result is that a shift to the Ni-Cd and NiMH EV platforms reduces lead discharges since the lead acid starter battery for the ICEV would be eliminated.

$\underline{PM_{10}}$

PM_{10} emissions are generally higher for the EVs than the ICEV. PM_{10} emissions from coal combustion and the increased mineral manufacturing for EV power packs is the cause. Table 16 indicates that a strong correlation exists between PM_{10} emissions and

EV energy requirements, thus supporting the conclusion that electricity production is a significant contributor to the EV's higher PM_{10} emissions. The model output shown in Figure 15 indicates that PM_{10} emissions will increase with EV use.

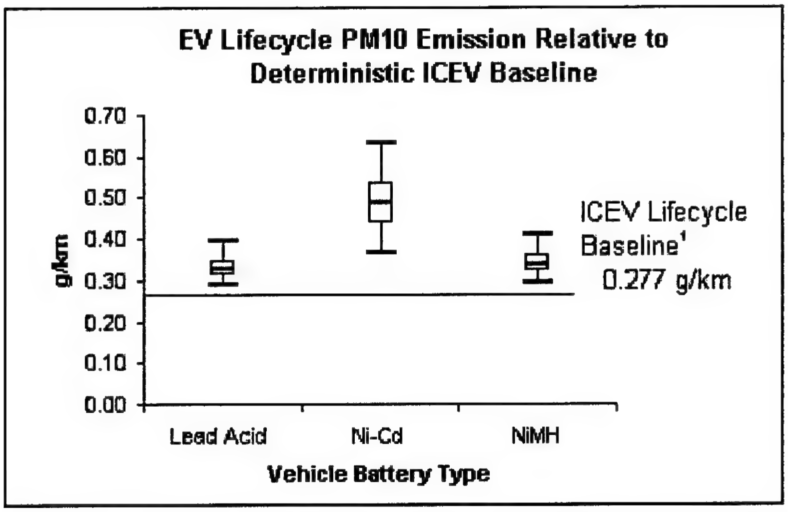

Figure 15. Electric Vehicle (EV) Lifecycle Particulate Matter Less than 10 microns in Diameter (PM_{10}) Emissions Relative to Deterministic Internal Combustion Engine Vehicle (ICEV) Baseline
[1]Baseline value from Sullivan *et al.*, 1998 total lifecycle PM_{10} emissions divided by a 120,000-mile lifecycle driving distance
PM_{10} = Particulate Matter less than 10 microns in diameter

Sullivan estimated total ICEV lifecycle unspecified particulate emissions at 0.277 g/km assuming a 120,000-mile lifetime (Sullivan,1998:12). Figure 15 shows PM_{10} emissions relative to Sullivan's estimate. Because these emissions occur outside urban areas, power plants, and mines, they may not be of great concern for public health impact.

Tables 6-7 Row #	Input Variable	Electric Vehicle (EV) Type		
		Lead Acid	Ni-Cd	NiMH
65	Vehicle Energy Requirement (Wh/km)	-0.69	-0.74	-0.70
69	Lead Acid Battery Energy Density (Wh/kg)	0.35	0.01	0.00
72	Lead Acid EV Range (km/charge)	-0.28	-0.01	-0.01
73	Ni-Cd EV Range (km/charge)	0.00	-0.13	-0.01
74	NiMH EV Range (km/charge)	0.00	0.00	-0.26
76	Battery Efficiency (%)	0.10	0.04	0.09
78	Vehicle Life (km)	0.18	0.08	0.16
77	Charger Efficiency (%)	0.08	0.03	0.07
Table 4	Lead Battery Lead Composition (%)	0.09	-0.02	0.00
66	Lead Acid Battery Life (km)	0.09	0.23	0.10
29	Lead Manufacturing PM_{10} Emission (g/kg)	-0.32	0.03	0.07
61	Electricity Production PM_{10} Emission (g/kWh)	-0.10	-0.04	-0.10
12	Aluminum Manufacturing PM_{10} Emission (g/kg)	-0.03	-0.03	-0.13
29	Copper Manufacturing PM_{10} Emission (g/kg)	-0.03	-0.12	-0.02
45	Nickel Manufacturing PM_{10} Emission (g/kg)	-0.01	-0.53	-0.24
61	Gasoline Production PM_{10} Emission (g/kg)	0.16	0.04	0.14

Table 16. Correlation of PM_{10} Emission Difference to Significant Input Variables

V. Analysis and Discussion

Analysis

The goal of this research was to determine which EV alternative most effectively addresses the three stated goals of recent automobile legislation. These three goals are (Clinton, 2000:1):

1. Reduction in greenhouse gas emissions
2. Reduction in criteria pollutant emissions
3. Reduction in foreign oil energy dependence

Table 17 summarizes the probabilities that each of the EV options will achieve the stated goals. Goal 1, a reduction in greenhouse gas emissions, is not achieved with certainty by any of the EV options. Goal 2, criteria pollutant emissions reduction, is achieved in some cases, with respect to some pollutants. Any of the EV options will achieve goal 3, reducing foreign oil dependence, by shifting transportation energy dependence to coal. Also, improvements in efficiency may be achieved with the EV, reducing total energy demand.

Table 17 summarizes the probability that the difference between the ICEV and each EV option will be favorable to the government's goal. These values are simply the probability that the EV will emit less pollution or use less energy per kilometer driven over its lifecycle.

	Probability of Achievement Relative to the Internal Combustion Engine Vehicle (ICEV) by Electric Vehicle (EV) Substitution		
Goal	**Lead Acid**	**Nickel Cadmium**	**Nickel Metal Hydride**
1. Reduction in greenhouse gas emissions			
	41%	34%	64%
2. Reduction in criteria pollutant emissions			
Sulfur oxides (SOx)	SOx emissions increase for all EV options.		
Carbon Monoxide (CO)	55%	82%	94%
Nitrogen oxides (NOx)	12%	12%	14%
Volatile Organic Compounds (VOCs)	66%	98%	100%
Lead Emissions	0%	98%	99%
Particulate Matter <10 μm Diameter (PM_{10})	<1%	0%	<1%
3. Reduction in foreign oil energy dependence			
	All EV options improve energy security by shifting the primary transportation sector energy source from petroleum to domestic coal.		
Reduction in Total Energy Consumption	76%	64%	91%

Table 17. Probability of Electric Vehicle (EV) Substitution Achieving Stated Goals

The magnitude of the differences in emissions is seen in a side-by-side comparison of the changes in pollutant emissions for the EV platforms in Figures 16 and 17. Figures 16 and 17 are the raw differences between the ICEV and EV as predicted by the model. As with the predicted emissions, the ends of the box represent the 25th and 75th percentile, the line within the box is the 50th percentile, and the "whiskers" are the observed values at the 2.5th and 97.5th percentile.

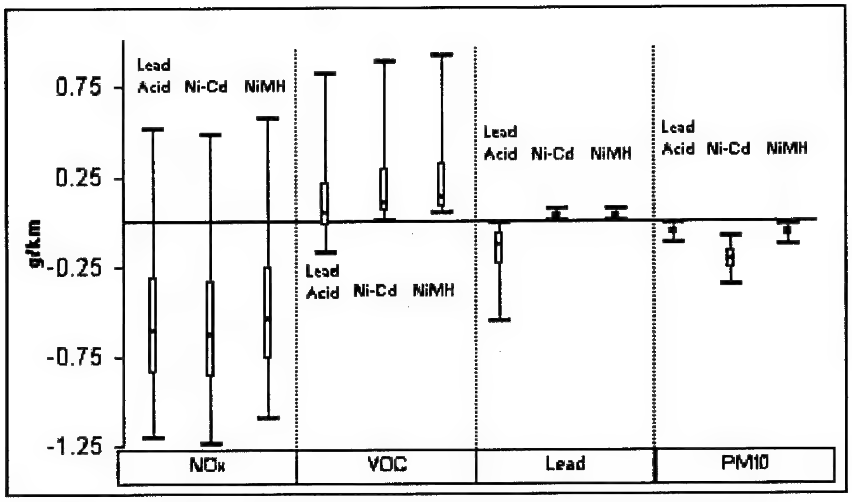

Figure 16. Range of Lifecycle Emissions Improvement Expected from a Shift to Electric Vehicles (EVs) from Internal Combustion Engine Vehicles (ICEVs) by EV Type

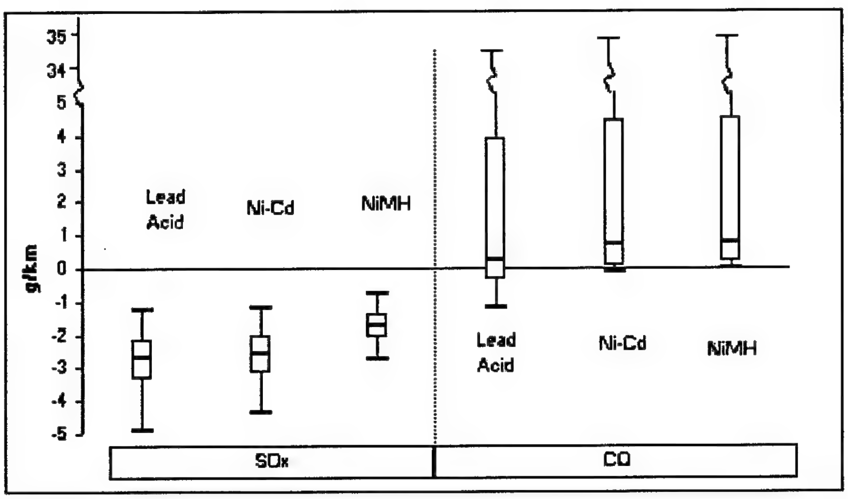

Figure 17. Range of Lifecycle Emissions Improvement Expected from a Shift to Electric Vehicles (EVs) from Internal Combustion Engine Vehicles (ICEVs) by EV Type

The relative impact of an emissions change must be evaluated before a decision can be made. For example, the decision maker responsible for choosing an EV option for a fleet may consider an increase in PM_{10} and lead emissions unimportant if they are far from humans. Conversely, a CO increase may be less desirable if it occurs in an urban

area. Similarly, SOx emissions are expected to increase, but as shown in Table 11 this increase is from metal and electricity production, which are also activities typically occurring outside urban areas.

The EV may not be the environmental panacea as first thought. The findings of this study are that the replacement of the ICEV with EV will result in a mixed impact with respect to the government's goals. The EV will reduce U.S. foreign oil dependence, and emissions of some criteria pollutants, but will increase others. The EV may benefit public health by relocating pollution from urban centers, where traffic is normally concentrated, to rural areas where electricity production and mining occur, but some emissions may actually increase as seen in Table 17.

When deciding which EV option to pursue, the relative impact of each emission, along with where the emission occurs and how mobile that pollutant is must be considered. There is no doubt that ICEV emissions in urban settings are having a detrimental effect on human health however, the EV may have an equally detrimental effect through indirect pollution. These factors must be weighed when deciding the direction of future transportation paradigms.

A shift to the EV will allow the U.S. to become less reliant on foreign oil by shifting to domestic coal. A drawback to the increased use of coal is the fact that coal emits more greenhouse gas per unit of energy generated. However, this increased emission may be offset by gains in efficiency.

Limitations and Future Research

The assumptions discussed in detail in this thesis result in limitations on the applicability of the result. For example, if the simplicity of the EV allows it to be assembled with much less environmental impact than the ICEV then some improvement in the EV lifecycle emissions can be expected. In addition, if great improvements were made in battery technology then the results of this thesis would no longer be valid.

The weighting of various emissions with respect to magnitude and location is not considered in this thesis. Future work should consider where the emissions occur and give greater weight to those that have a direct pathway to humans or are particularly detrimental to the natural environment. The mobility of pollutants should also be considered, as SOx, a pollutant sure to increase, will form acid rain that has impacts far removed from the source.

Future research should evaluate the emissions of a hybrid vehicle design, a vehicle with both an internal combustion engine and large storage batteries. Hybrid vehicles like the Honda Insight are enjoying success in the consumer market and have performance capabilities on a par with the ICEV. These vehicles therefore, will probably be a suitable replacement for the ICEV.

Another area of future research should be foreign mineral dependence. The increased amount of raw materials required for an electric or hybrid vehicle drive system may result in a shift from foreign oil dependence to an equally undesirable foreign

mineral dependence. The government must be careful to avoid blindly trading one form of insecurity for another.

Conclusion

Lifecycle assessments are difficult and often expensive. Through simplifying assumptions, this thesis has accomplished an emissions and inputs evaluation on three types of EVs that should allow the decision maker responsible with selecting an EV alternative to make a more informed and environmentally sound decision that complies with both the letter and intent of the law. This thesis demonstrates that transportation options should not be implemented without careful study of the entire lifecycle impact or unexpected detrimental impacts may occur. Probabilities indicate that substitution of the EV for the ICEV, given current industry practices, will reduce foreign oil dependence, volatile organic carbon and lead emissions, but the other emissions studied will increase while greenhouse gasses remain essentially unchanged.

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Vita

Captain David L. McCleese graduated from Lewis County High School in Lewis County, Kentucky in May 1987. During High School, he attended Foster "Sid" Meade Vocational School for two years and was certified as a Plymouth Auto Mechanic. After graduating high school, he joined the United States Navy and was assigned to the USS Brooke FFG-1, home ported in San Diego California from 1988-1989 as an Engineman Apprentice. After decommissioning the Brooke, he served aboard the USS Fife DD-991, home ported in Yokosuka Japan from 1989 – 1990 as a Gas Turbine Systems Technician achieving the rank of Petty Officer Second Class (E-5). In 1990, he left active duty and entered the Naval Reserve where he served as leading Petty Officer for the Shore Intermediate Maintenance Facility Norfolk augmentation unit in Lexington Kentucky and achieved the rank of Petty Officer First Class (E-6). In 1991, he entered undergraduate studies at the University of Kentucky in Lexington Kentucky where he graduated with a Bachelor of Science degree in Mechanical Engineering in May 1996. Also in May 1996, he left the Naval Reserve and was commissioned as a Second Lieutenant in the US Air Force through the Officer Training School at Maxwell Air Force Base in October of the same year. His first Air Force assignment was at Yokota Air Base Japan, 374th Civil Engineer Squadron. In 1999, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, he will be assigned to the 15th Civil Engineer Squadron in Hickam Hawaii.

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14. ABSTRACT

The U.S. Federal Government has encouraged shifting from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs) with three objectives, reducing U.S. foreign oil dependence, greenhouse gas emissions, and criteria pollutant emissions. This thesis uses Monte Carlo simulation to predict lifecycle emissions and energy consumption differences per kilometer driven from replacing ICEVs with three EV options: lead acid, nickel cadmium (Ni-Cd), and nickel metal hydride (NiMH). All three EV options reduce U.S. foreign oil dependence by shifting to domestic coal. The probability that EV's lifecycle energy consumption per km driven are lead acid 76%, Ni-Cd 64%, and NiMH 90%. The probabilities that EV substitution reduce global warming gas emissions are lead acid 41%, Ni-Cd 34%, and NiMH 64%. All three EV options increase sulfur oxides emissions. The probably that EV substitution will decrease nitrogen oxides emissions are only 12-14%. The probability that EV substitution reduces particulate matter emissions is less than one percent. The probability that EV substitution reduces volatile organic carbon emissions is lead acid 66%, Ni-Cd 98%, and NiMH 100%. Probabilities indicate that EVs will reduce foreign oil dependence, volatile organic carbon and lead emissions. However the other air emissions will increase and greenhouse gas emissions remain relatively unchanged.

15. SUBJECT TERMS

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